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STUDY OF SIZE EFFECTS ON VTOL HANDLING QUALITIES CRITERIA

Lockheed Report No. 18408

By

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I. H. Culver
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September 1965

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-236(T)
LOCKHEED-CALIFORNIA COMPANY

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The following report has been reviewed by the U. S. Army Aviation Materiel Laboratories and is considered to be technically sound.

Definition of handling qualities criteria, from minima acceptable to optima desired, becomes increasingly important as aircraft become larger and more complex and expensive. The questions are of particular concern in VTOL aircraft, where weight and energy penalties associated with control demands in hovering and low-speed flight generally represent greater sacrifices in range-payload capabilities than on other vehicles.

This report is intended to clarify fundamental relationships involving size, design, and handling qualities and thereby to provide a rational framework within which work may proceed on specific design and mission analyses.

Comments, in the form of criticisms or elaborations of the information presented, are invited.

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For

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ABSTRACT

A fundamental study is presented of the effects of vehicle size on handling qualities of jet and helicopter-type VTOL aircraft at hover and low speeds, size being defined by the characteristic linear dimension. The effects of size on vehicle handling qualities capability and pilot-vehicle compatibility are developed. Consideration is given to the pilot as an adaptive nonlinear servo.

The study indicates:

1. Control power/inertia and damping/inertia tend to decrease with size.
2. Except for tail rotor helicopters in yaw, final angular rates are relatively invariant with size.
3. Characteristic time to reach final angular rate increases with size.
4. Linear accelerations and motions are nearly invariant with size.
5. Effects of external disturbances and trim changes with speed on jet VTOL vehicles decrease at least as rapidly as control power/inertia.

PREFACE

This report describes and presents essential elements and conclusions of work called for under Contract DA 44-177-AMC-236(T), Study of Effect of Size on VTOL Handling Qualities Criteria. This effort was accomplished during the period 30 June through 30 November 1964 by Lockheed-California Company for the United States Army Aviation Materiel Laboratories, Fort Eustis, Virginia. The study was conducted by Messrs. J. F. Johnston, I. H. Culver, and C. F. Friend of Lockheed. Mr. R. R. Piper was the authorized representative of the United States Army Contracting Officer for this work. Assistance has been provided during this period by the VTOL Branch, Flight Mechanics and Technology Division, of the NASA Langley Research Center.

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SYMBOLS

In order to provide a common basis for describing characteristics relating to VTOL handling qualities criteria, the following terminology and definitions are provided. Symbols and definitions are in accordance with those given in "Letter Symbols for Aeronautical Science" (Reference 1) prepared in collaboration with the National Advisory Committee on Aeronautics (currently National Aeronautics and Space Administration), Institute of Aeronautical Science, and American Rocket Society (IAS and ARS are currently the American Institute of Aeronautics and Astronautics), and sponsored by the American Society of Mechanical Engineers.

The characteristic dimension, considering the nature of this study as a similitude analysis, is designated l. Objects, such as vehicles, are located by coordinates x, y, and z measured from x, y, and z axes of a point on the earth's average surface. Vehicle attitude is designated by angles θ, ϕ, and ψ with respect to earth reference axes and vehicle reference axes. Velocities and accelerations are indicated by dot and double dot superscripts to the basic coordinates and angles ($\dot{x}$, $\dot{y}$, $\dot{z}$, $\dot{\theta}$, $\dot{\phi}$, $\dot{\psi}$ and $\ddot{x}$, $\ddot{y}$, $\ddot{z}$, $\ddot{\theta}$, $\ddot{\phi}$, $\ddot{\psi}$). Errors introduced by using earth axes in lieu of wind and inertia axes in determination of forces and moments on vehicles is neglected on the basis that such errors will be common to all vehicles.

Differences or changes in quantities are indicated by the prefix Δ. Position, velocity, and acceleration errors are designated by the subscript ϵ. Position, velocity, and acceleration at pilot's eye are noted by the subscript e. Position, velocity, and acceleration perceived by the pilot's sensory system and errors pertinent to perception are indicated by the subscript p. Thus the error in distance parallel to the x axis to an object perceived by the pilot would be x_{ϵ_p}.

Symbol		Units
A	Rotor disk area	ft.^{2}
a	Rotor blade lift curve slope	none
A_j	Jet inlet or exhaust area	ft.^{2}
b	Wing span	ft.
b	Number of blades	none
C	Vehicle angular damping	ft.lb.sec./rad.
C_D	Vehicle drag coefficient	none
C_{D_V}	Vehicle vertical drag coefficient	none
C_H	Vehicle horizontal damping	lb.sec./ft.
C_m	Vehicle moment coefficient	none
C_V	Vehicle vertical damping	lb.sec./ft.
c	Rotor blade chord	ft.
$\overline{c}$	Wing mean aerodynamic chord	ft.
d	Derivative	none
D_j	Jet inlet or exhaust diameter	ft.
e	Equivalent rotor hinge offset	ft.
F	Force	lb.
F_C	Control force	lb.
F_{C_H}	Horizontal control force	lb.
F_{C_V}	Vertical control force	lb.
F_H	Horizontal force	lb.
F_V	Vertical force	lb.
g	Acceleration of gravity	ft./sec.^{2}

Symbol		Units
h	Height above ground	ft.
h	Vertical offset of rotor	ft.
h_e	Equivalent vertical offset of rotor	ft.
I, I_x, etc.	Moment of inertia for axis noted	ft.lb.sec.^{2}
J_G	Gyro polar moment of inertia	ft.lb.sec.^{2}
J_R	Rotor polar moment of inertia	ft.lb.sec.^{2}
K, K_1, etc.	Constants	none
K_β	Rotor stiffness	ft.lb./rad.
L	Characteristic length	ft.
M	Moment applied to vehicle	ft.lb.
M_A	Aerodynamic moment applied to rotor	ft.lb.
M_c	Control moment applied to vehicle	ft.lb.
M_d	Damping moment applied to vehicle	ft.lb.
M_G	Gyroscope precessional moment applied to rotor	ft.lb.
q	Dynamic pressure	lb./ft.^{2}
R	Rotor radius	ft.
$\bar{R}$	Radius to rotor blade center of gravity	ft.
r	Radius of rotor blade element	ft.
S	Wing area	ft.^{2}
T	Thrust	lb.
t	Time	sec.
V	Velocity	ft./sec.
V_e	Entry velocity	ft./sec.

Symbol		Units
V_g	Gust velocity	ft./sec.
V_H	Vehicle horizontal velocity	ft./sec.
V_j	Jet velocity	ft./sec.
V_V	Vehicle vertical velocity	ft./sec.
v	Induced velocity through rotor	ft./sec.
W	Vehicle weight	lb.
W_R	Rotor weight	lb.
x, y, z	Earth axes or vehicle axes coordinates	ft.
x_{CG}	Distance from vertical thrust axis to vehicle center of gravity	ft.
α	Angle of attack	rad.
α_b	Rotor blade angle of attack	rad.
β_o	Rotor blade coning angle	rad.
δ	Rotor blade profile drag coefficient	none
Δ	Increment	none
θ	Vehicle pitch angle	rad.
θ_c	Rotor blade cyclic pitch angle	rad.
θ_t	Rotor blade tip collective pitch angle	rad.
θ_R	Rotor tilt angle	rad.
θ_1	Vehicle pitch angular displacement in 1 second	rad.
λ	Inflow ratio, $(V \sin \alpha - v)/\Omega R$	rad.
μ	Rotor tip speed ratio, $(V \cos \alpha)/\Omega R$	rad.
ρ	Air mass density	$lb.sec^2/ft^4$

Symbol		Units
τ	Vehicle response time	sec.
τ_H	Vehicle response time for horizontal motion	sec.
τ_V	Vehicle response time for vertical motion	sec.
ϕ	Roll angle	rad.
$\dot{\phi}_D$	Desired roll angular velocity	rad./sec.
ϕ_t	Rotor tip inflow angle, $v/\Omega R$	rad.
ϕ_1	Roll angular displacement in 1 second	rad.
$\phi_{1/2}$	Roll angular displacement in 1/2 second	rad.
ψ	Yaw angle	rad.
$\dot{\psi}_D$	Desired yaw angular velocity	rad./sec.
ψ_1	Yaw angular displacement in 1 second	rad.
Ω	Rotor angular velocity	rad./sec.
ω	Frequency	rad./sec.

Single dot indicates velocity

$\dot{x}, \dot{y}, \dot{z}, \dot{\theta}, \dot{\phi}, \dot{\psi}$

Double dot indicates accelerations

$\ddot{x}, \ddot{y}, \ddot{z}, \ddot{\theta}, \ddot{\phi}, \ddot{\psi}$

Subscripts

H	Horizontal
j	Jet
V	Vertical

SUMMARY

This report is a fundamental study of the effects of vehicle size on the handling qualities of jet and helicopter type VTOL aircraft at hover and low speeds. Size in this connection refers to the size of a characteristic linear dimension. The basic handling quality characteristics are defined in terms of the ratios of control power to inertia (initial vehicle acceleration response to control input) and of the vehicle damping to inertia. The final response rate is the ratio of the control power to the damping.

Based on existing design trends, it is found that the angular control power/inertia and damping/inertia of these vehicles tend to decrease with increasing size, while the final angular rates obtainable tend to be relatively invariant with size. An exception is helicopter yaw rate due to tail rotor, which decreases with increasing size. The characteristic time to reach the final angular rate increases with size.

Linear accelerations and motions due to control inputs were found to be nearly invariant with size, including vertical and horizontal vehicle accelerations and pilot linear accelerations due to vehicle angular accelerations. This result indicates that mission capability (the ability of the vehicle to perform maneuvers essential to the assigned task) is not diminished appreciably by the reduced angular acceleration capability with increasing size.

The effects of external disturbances and trim changes with speed on jet VTOL vehicles were found to decrease at least as rapidly as the control power/inertia with increasing size. This will result in increasing angular accuracy with increasing size in the presence of disturbances. For helicopters, the rotor tilt response rate to external disturbances is invariant with size, but airframe angular accelerations decrease with size, again indicating increasing angular accuracy with increasing size in the presence of disturbances.

The effects of size on pilot-vehicle compatibility are developed by consideration of the pilot as an adaptive nonlinear servo as suggested by other investigators. It is indicated that the pilot, having a relatively fixed perception-reaction time, will have the most trouble flying very small vehicles or others having excessive control power/inertia, and that his angular accuracy will tend to increase with increasing vehicle size. Some simplified relations are also developed to show

pilot and servo system limitations in providing vehicle damping, and their relationship to vehicle size. These considerations also reinforce other investigators' conclusions that complete blind operation of VTOL aircraft, including takeoff and landing, is possible with data presentation that minimizes the pilot's perception-reaction time.

It is suggested that research be continued with present variable-stability VTOL research vehicles, both jet and helicopter, using special control systems to synthesize the acceleration response to disturbances and trim changes with speed of any size vehicle from very small to very large. Control power and damping criteria can then be determined experimentally as a function of size. Areas in which simulation is not complete are also discussed.

CONCLUSIONS

On the basis of a study of the variation with size of jet and helicopter VTOL aircraft angular and linear acceleration and damping capability, response to disturbances, and the pilot function, it is concluded that:

1. Angular control power/inertia and damping/inertia decrease with increasing size, while the final angular rates for a given control deflection are relatively invariant with size. Yaw rate of a tail-rotor type helicopter, however, decreases with size (Table 1).

2. Linear accelerations and motions due to control inputs are relatively invariant with size (Table 1).

3. Vehicle angular accelerations due to external disturbances decrease with increasing size (Table 1).

4. Mission capability (ability to perform maneuvers essential to accomplishment of assigned task) is not diminished appreciably by these inherent variations with size; however, the physical size of large vehicles will limit them to larger holes and channels than those in which smaller vehicles can fly.

5. Angular accuracy in the presence of disturbances improves with increasing size. Angular accuracy is not greatly improved by augmenting vehicle damping unless the inertia/damping value provided (the reciprocal of the damping gain) is less than the pilot's perception-reaction time.

6. Development of handling quality criteria (requirements or regulations) including effects of size is dependent on obtaining quantitative limitations on the pilot and servo functions in providing damping. These limitations can be expressed in terms of pilot or servo system lag time as observed by other investigators.

7. The amount of damping available from thrust modulation involving engine or lift fan speed variations tends to be limited by the time lag in varying thrust which increases with engine size.

8. Methodology for investigation of the effects of size on handling qualities developed herein and by others appears to be applicable to related fields such as development of data presentation for the pilot, flight control systems, methods to reduce learning time and error susceptibility, etc.

9. Variable-stability VTOL research vehicles can be adjusted to represent the major effects of size for experimental determination of the variation of desirable handling qualities criteria with size.

TABLE 1

EFFECT OF SIZE ON VEHICLE BASIC HANDLING CAPABILIT

VEHICLE		JET VTOL			
Capability	Axis	Vertical (Yaw)	Longitudinal and Lateral (Pitch and Roll): Jets Located Proportional to Jet Diameter	Longitudinal and Lateral (Pitch and Roll): Jets Located Proportional to Vehicle Size	Vertical (Yaw)
Control Power / Mass (Linear Motions)	Ft/Sec^2	Constant	Constant	Constant	$1/(K_1 + L^{\frac{1}{2}})$ (4) Constant (5)
Damping / Mass (Linear Motions)	1/Sec	K + 1/L Constant(8)	K + 1/L Constant (8)	Constant (8) K + 1/L	$1/(K_1 + L^{\frac{1}{2}})$ (4) Constant (5)
Response Time (Linear Motions)	Sec	1/(K + 1/L) Constant(8)	Constant (8) 1/(K + 1/L)	Constant (8) 1/(K + 1/L)	$K_1 + L^{\frac{1}{2}}$ (4) Constant (5)
Angular Control Power / Inertia	Rad/Sec^2	1/L	1/L	1/L	$1/(K_6L + L^{3/2})$ (4) 1/L (5)
Angular Damping / Inertia	1/Sec	1/L	1/L	1/L	$1/(K_6 + L^{\frac{1}{2}})$ (4) Constant (5)
Angular Response Time	Sec	L	L	L	$K_6 + L^{\frac{1}{2}}$ (4) Constant (5)
Angular Velocity	Rad/Sec	Constant	Constant	Constant	1/L
Angular Acceleration Caused by a Wind or Gust	$\frac{Rad/Sec^2}{Ft/Sec}$	$1/L^2$	$K_9/L + K_{11}/L^{\frac{1}{2}}$	$K_9/L^2 + K_{10}/L$	$1/(K_6L + L^{3/2})$ (4) 1/L (5)
Control Displacement to Counter a Wind or Gust	Rad	-	-	-	Constant
Acceleration Caused by Engine Failure	Rad/Sec^2	-	$1/L^{\frac{1}{2}}$	1/L	-

…DLING CAPABILIT…

Vertical (Yaw)	
… + $L^{\frac{1}{2}}$)	(4)
…ant	(5)
… + $L^{\frac{1}{2}}$)	(4)
…ant	(5)
$L^{\frac{1}{2}}$	(4)
…ant	(5)
…L + $L^{3/2}$)	(4)
	(5)
… + $L^{\frac{1}{2}}$)	(4)
…nt	(5)
…$^{\frac{1}{2}}$	(4)
…nt	(5)
…/L	
… + $L^{3/2}$)	(4)
…/L	(5)
…nt	
-	

TABLE 1

EFFECT OF SIZE ON VEHICLE BASIC HANDLING CAPABILITIES

JET VTOL			HELICOPTERS		
…al	Longitudinal and Lateral (Pitch and Roll)		Vertical (Yaw)	Longitudinal and Lateral (Pitch and Roll)	
	Jets Located Proportional to Jet Diameter	Jets Located Proportional to Vehicle Size		Articulated Rotor	Rigid Rotor
…nt	Constant	Constant	$1/(K_1 + L^{\frac{1}{2}})$ (4) Constant (5)	$1/(K_1 + L^{\frac{1}{2}})$ (4) Constant (5)	$1/(K_1 + L^{\frac{1}{2}})$ Consta…
…L …t(8)	$K + 1/L$ Constant (8)	Constant (8) $K + 1/L$	$1/(K_1 + L^{\frac{1}{2}})$ (4) Constant (5)	$K_3 + K_4L^{\frac{1}{2}} + K_5L + L^2$ (4) $K_3 + K_4 + K_5 + L^2$ (5)	$K_3 + K_4L^{\frac{1}{2}} + K_5L +$ … $K_3 + K_4 + K_5 + L^2$
…1/L …t(8)	Constant (8) $1/(K + 1/L)$	Constant (8) $1/(K + 1/L)$	$K_1 + L^{\frac{1}{2}}$ (4) Constant (5)	$1/(K_3 + K_4L^{\frac{1}{2}} + K_5L + L^2)$ (4) $1/(K_3 + K_4 + K_5 + L^2)$ (5)	$1/(K_3 + K_4L^{\frac{1}{2}} + K_5$ … $1/(K_3 + K_4 + K_5 +$ …
	$1/L$	$1/L$	$1/(K_6L + L^{3/2})$ (4) $1/L$ (5)	$1/L + K_8/L^2$ (7)	$1/L + K_8/L^2$
	$1/L$	$1/L$	$1/(K_6 + L^{\frac{1}{2}})$ (4) Constant (5)	$1/L + K_8/L^2$ (7)	$1/L + K_8/L^2$
	L	L	$K_6 + L^{\frac{1}{2}}$ (4) Constant (5)	$L^2/(K_8 + L)$ (7)	$L^2/(K_8 + L)$
…nt	Constant	Constant	$1/L$	Constant	Constar…
	$K_9/L + K_{11}/L^{\frac{1}{2}}$	$K_9/L^2 + K_{10}/L$	$1/(K_6L + L^{3/2})$ (4) $1/L$ (5)	$1/L + K_8/L^2$ (6)	$1/L + K_8/L^2$
	-	-	Constant	Constant	Constan…
	$1/L^{\frac{1}{2}}$	$1/L$	-	-	-

B

HELICOPTERS

Longitudinal and Lateral (Pitch and Roll)

Rigid Rotor	Articulated Rotor		Rigid Rotor	
		(4)	$1/(K_1 + L^{\frac{1}{2}})$	(4)
onstant	Constant	(5)	Constant	(5)
$K_5L + L^2$	$K_5L + L^2$	(4)	$K_3 + K_4L^{\frac{1}{2}} + K_5L + L^2$	(4)
$+ L^2$	$K_5 + L^2$	(5)	$K_3 + K_4 + K_5 + L^2$	(5)
$+ K_5L + L^2)$	$L^{\frac{1}{2}} + K_5L + L^2)$	(4)	$1/(K_3 + K_4L^{\frac{1}{2}} + K_5L + L^2)$	(4)
$K_5 + L^2)$	$+ K_5 + L^2)$	(5)	$1/(K_3 + K_4 + K_5 + L^2)$	(5)
		(7)	$1/L + K_8/L^2$	(7)
		(7)	$1/L + K_8/L^2$	(7)
		(7)	$L^2/(K_8 + L)$	(7)
onstant	Constant		Constant	
		(6)	$1/L + K_8/L^2$	(6)
nstant	Constant		Constant	
-	-		-	

(1) For translational motions.

(2) L is the characteristic length.

(3) Independent of rotor disk loading unless otherwise noted.

(4) Rotor disk loading proportional to size.

(5) Rotor disk loading constant.

(6) Rotor precession velocity invariant.

(7) K_8 proportional to equivalent hinge offset.

(8) For hovering

C

RECOMMENDATIONS

This brief fundamental study has indicated a number of areas for further research and a methodology for guiding and interpreting such research. It is recommended that:

1. The primary effects of size (control power/inertia, damping/inertia, and response to external disturbances) be simulated on existing variable-stability jet and helicopter VTOL aircraft by methods indicated herein for experimental determination of desirable and minimum handling qualities criteria as a function of vehicle size. Although some experimental data have been obtained showing the effects of external disturbances (expecially aerodynamic moment derivatives/inertia as described in Appendix IV), much more is required to properly define criteria for regulations covering a broad spectrum of aircraft. Particularly, information is lacking on the effect of aerodynamic moments with respect to vertical velocity/inertia and the effect of higher wind and gust velocities (higher than 25 knots). In addition, the effect of physical size in such terms as distance to visible extremities, pilot distance to center of gravity, etc., should be investigated.

2. Applications and extensions of the method of examining the pilot function as an adaptive servo limited by his (variable) time lag should be further developed by investigators in the various fields to which it may be applicable. These include vehicle handling quality criteria (regulations), including effect of size, data presentation, IFR flight, learning time, error susceptibility, etc.

   a. Research should be conducted on the magnitude and variation of the pilot time constant and adaptive lag under a wide variety of simulated flight conditions and vehicle characteristics, including size effects.

   b. Adequacy of data presentation should be evaluated by its effectiveness in reducing pilot time constant and adaptive lag under multiaxis control conditions.

   c. An integrated IFR data presentation should be developed to permit blind takeoffs and landings of VTOL aircraft.

INTRODUCTION

Evaluation of theoretical and experimental documentary material relative to current VTOL handling qualities criteria, References 2, 3, and 4, has shown evidence of the need for further investigation of the applicability of these criteria. A particular area of interest is the effect of vehicle size on the criteria. Provisional AGARD recommendations (Reference 3) for V/STOL aircraft in general and U.S. Military Specification MIL-H-8501A for helicopters are based on the assumption that the linear displacement of the vehicle extremity (wing tip, nose, or tail) resulting from rotational motion commanded by a unit of control input in a unit time should be constant (irrespective of vehicle size). Other authorities, References 5 and 6, contend that this assumption is not valid and suggest other criteria such as the maintenance of constant angular velocity for a unit of pilot applied control force and unit time.

The object of the present work performed under Contract DA 44-177-AMC-236(T) is to investigate these and other effects of size on vehicle handling qualities criteria using dimensional analysis, laws of similitude, basic aerodynamics, and human factors relationships. Comparison is made of various handling criteria. Determination is made of the effect of these criteria on the operational and/or design implications with respect to vehicles of various sizes up to 100,000 pounds gross weight.

Principal handling qualities requirements or recommendations of published References 2, 3, 4, and 5 are summarized in Table 2. In order to compare these criteria effectively, it is necessary to transform parameters of some of these references to parameters common to all four. Damping/inertia and control power/inertia were selected as common basic parameters because these terms are readily comprehensible. These parameters are directly related to other characteristics such as response time, angular acceleration, angular rate. Effects of control power/inertia and damping/inertia on operation and design can easily be determined.

Figures 1, 2, and 3 show damping/inertia values determined from References 2, 3, 4, and 5 for typical VTOL vehicles of various gross weights. Instrument flight (IFR) visual flight (VFR), and emergency (single failure of engine, power control system, or stability augmentation system) conditions are represented where applicable in Figures 1, 2, and 3,

TABLE 2

PRINCIPAL HANDLING QUALITIES CRITERIA FOR VTOL VEHICLES (1)

Axis	Source / Condition	MIL-H-8501A, Ref. 2 (2) Control		AGARD 408, Ref. 3 (5) Control		TN D-1328, Ref. (7) Control		D
		Control	Damping	Control	Damping	Control		
Longitudinal	IFR	$\theta_1 \ge \frac{5.10}{(W + 1000)^{1/3}}$	$C \ge 15I_y^{.7}$	$\theta_1 \ge \frac{5.24}{(W + 1000)^{1/3}}$	$C \ge 15I_y^{.7}$	(6)		
	VFR	$\theta_1 \ge \frac{3.14}{(W + 1000)^{1/3}}$	$C \ge 8I_y^{.7}$	(6)	(6)	$M_c/I \ge .6$ $M_c/I \le 2.2$	(9)	C/I =
	EMERGENCY (3)	(6)	(6)	$\theta_1 \ge \frac{3.14}{(W + 1000)^{1/3}}$	$C \ge 8I_y^{.7}$	(6)		
Lateral	IFR	$\phi_{\frac{1}{2}} \ge \frac{1.67}{(W + 1000)^{1/3}}$ $\dot{\phi} \le 0.349,\ \delta_a = 1$	$C \ge 25I_x^{.7}$	$\phi_1 \ge \frac{5.24}{(W + 1000)^{1/3}}$ $\phi_1 \ge 0.175$ $\phi_1 \le 0.349,\ \delta_a = 1$	$C \ge 25I_x^{.7}$	(6)		
	VFR	$\phi_{\frac{1}{2}} \ge \frac{1.41}{(W + 1000)^{1/3}}$ $\dot{\phi} \le 0.349,\ \delta_a = 1$	$C \ge 18I_x^{.7}$	(6)	(6)	$M_c/I \ge 1.8$ $M_c/I \le 4.0$	(9)	C/I =
	EMERGENCY (3)	(6)	(6)	$\phi_1 \ge \frac{5.24}{(W + 1000)^{1/3}}$ $\phi_1 \ge 0.175$ $\phi_1 \le 0.349,\ \delta_a = 1$	$C \ge 18I_x^{.7}$	$M_c/I \ge 0.7$ $M_c/I \le (6)$	(10)	C/I =
Directional	IFR	$\psi_1 \ge \frac{5.76}{(W + 1000)^{1/3}}$ $\psi_1 \le 0.873,\ \delta_r = 1$ (4)	$C \ge 27I_z^{.7}$	$\psi_1 = \frac{3.14}{(W + 1000)^{1/3}}$	$C \ge 27I_z^{.7}$	(6)		
	VFR	$\psi_1 \ge \frac{5.76}{(W + 1000)^{1/3}}$ $\psi_1 \le 0.873,\ \delta_r = 1$ (4)	$C \ge 27I_z^{.7}$	(6)	(6)	$M_c/I \ge 0.7$ $M_c/I \le (6)$	(9)	C/I
	EMERGENCY (3)	(6)	(6)	$\psi_1 = \frac{3.14}{(W + 1000)^{1/3}}$	$C \ge 14I_z^{.7}$	$M_c/I \ge 0.25$ $M_c/I \le (6)$	(10)	C/I

OL VEHICLES (1)

D-1328, Ref. 4 (7)		Curry & Matt., Ref. 5 (11)	
ol	Damping (8)	Control	Damping
)	(6)	$\dot{\theta}_D = 0.349$ (5) $0.175 \le \dot{\theta} \le 0.699$	$\tau_D = 0.5$ (5) $0.1 \le \tau \le 1.0$
(9)	C/I = 0.5 (9)	(6)	(6)
	(6)	(6)	(6)
	(6)	$\dot{\phi}_D = 0.611$ $0.367 \le \dot{\phi} \le 0.916$	$\tau_D = 0.4$ $0.1 \le \tau \le 1.0$
(9)	C/I = 2.0 (9)	(6)	(6)
(10)	C/I = 2.0 (10)	(6)	(6)
	(6)	$\dot{\psi}_D = 1.570$ (2) $1.046 \le \dot{\psi} \le 2.617$	$\tau_D = 0.5$ (2) $0.1 \le \tau \le 1.5$
(9)	C/I = 0.7 (9)	(6)	(6)
(10)	C/I = [illegible].7 (10)	(6)	(6)

(1) Expressions define the control power and damping required to produce vehicle motion with full control (obviously control power required for equilibrium trim is additional to these criteria), unless noted.

(2) For hover.

(3) For safe operation including landing.

(4) $\phi_1 = 192/(W + 1000)^{1/3}$ starting at $\dot{x} = \dot{y} = \dot{\phi} = 0$ with 35 KN critical wind.

(5) $0 \le \dot{x} \le$ Conversion.

(6) Unspecified.

(7) -30 KN $\le \dot{x} \le 30$ KN and 20 KN $\le \dot{y} \le 20$ KN.

(8) C/I for M_c/I = MINIMUM.

(9) Cooper Pilot Rating = 3.5.

(10) Cooper Pilot Rating = 6.5.

(11) Helicopter $0 \le \dot{x} \le$ Conversion, Modified CPR = 3.5.

(12) All expressions were taken directly from the sources listed except angles are expressed in radians to provide consistency.

B

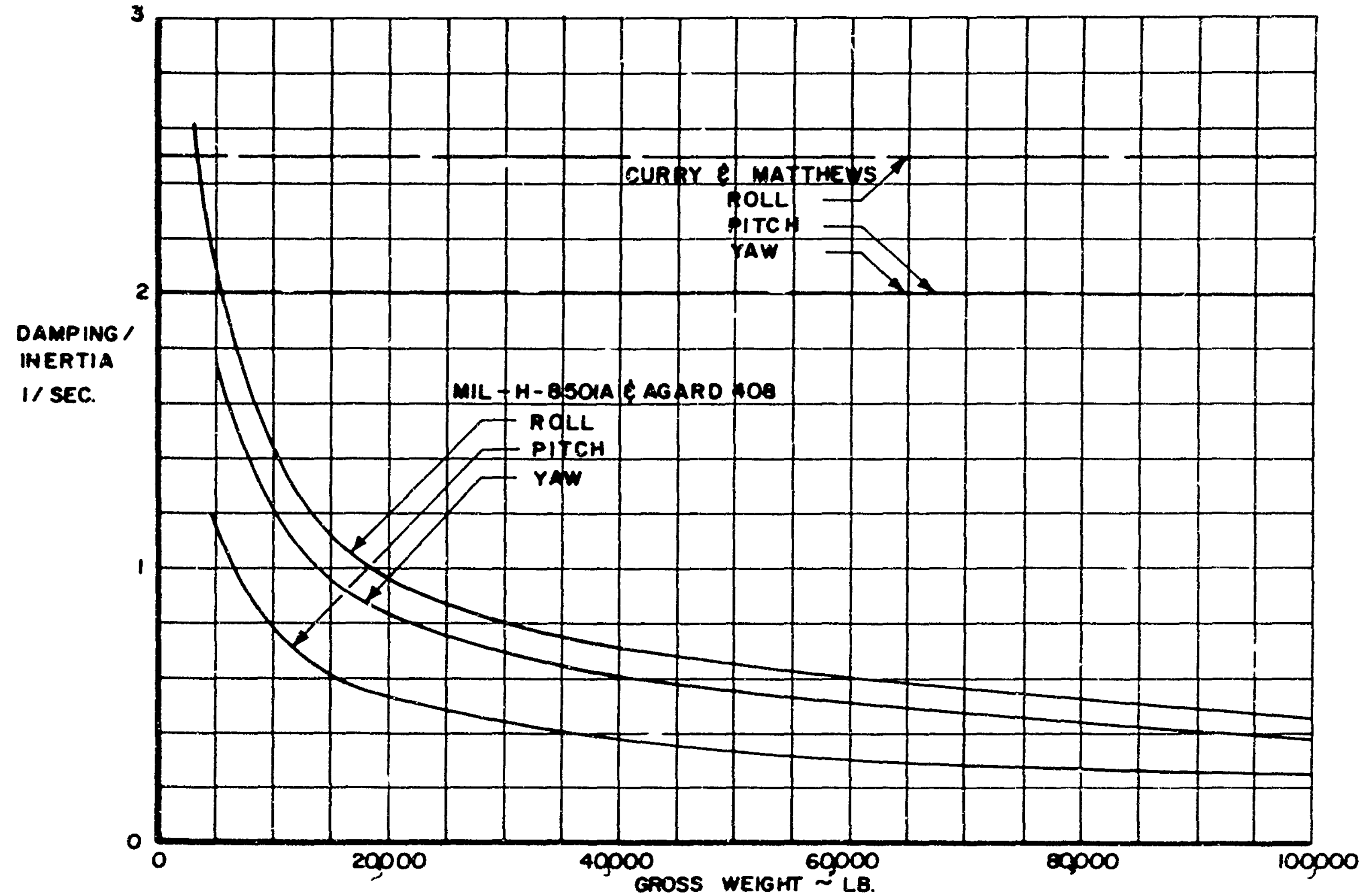


Figure 1 - Damping/Inertia, IFR

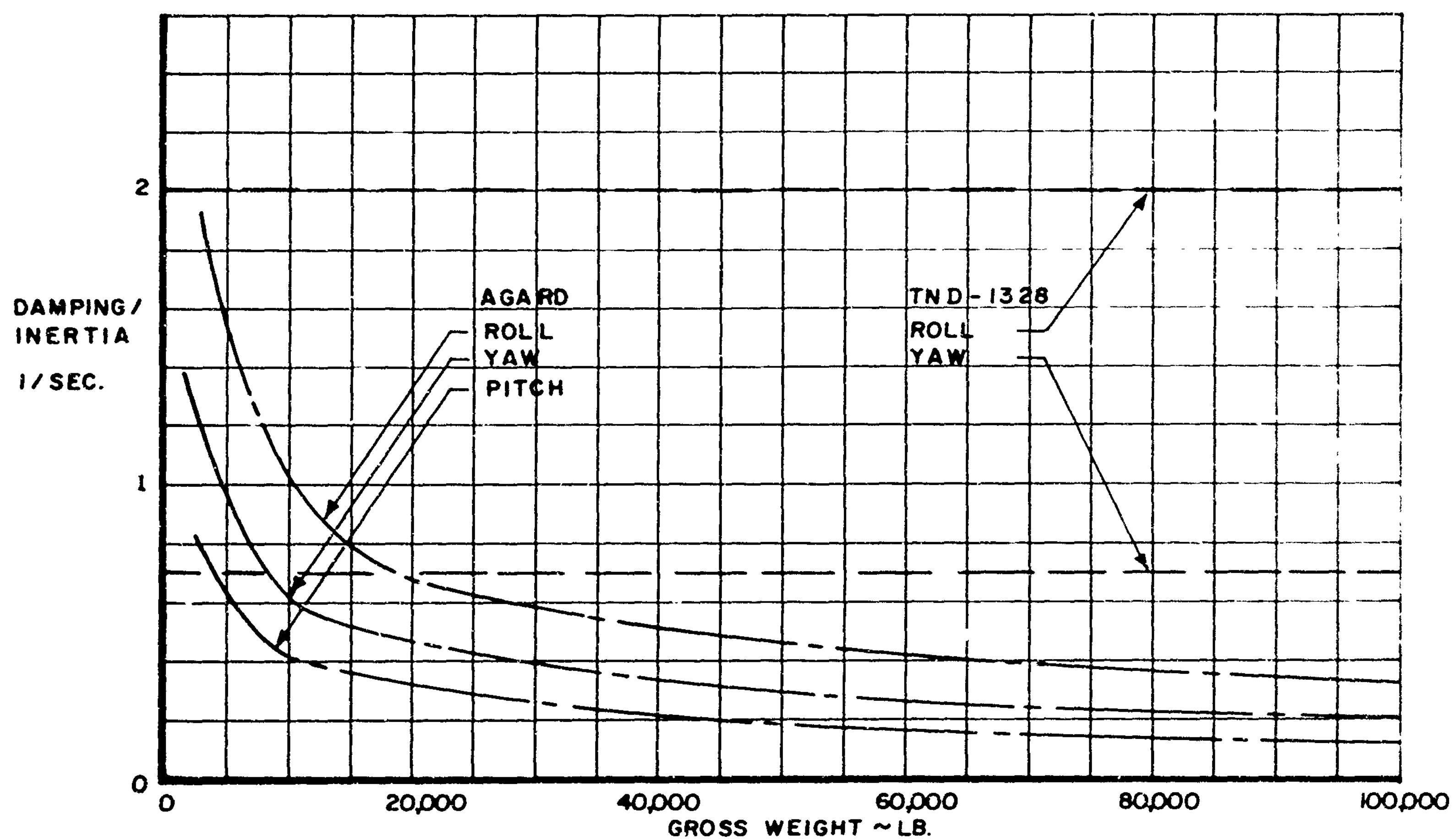


Figure 3 - Damping/Inertia, Emergency

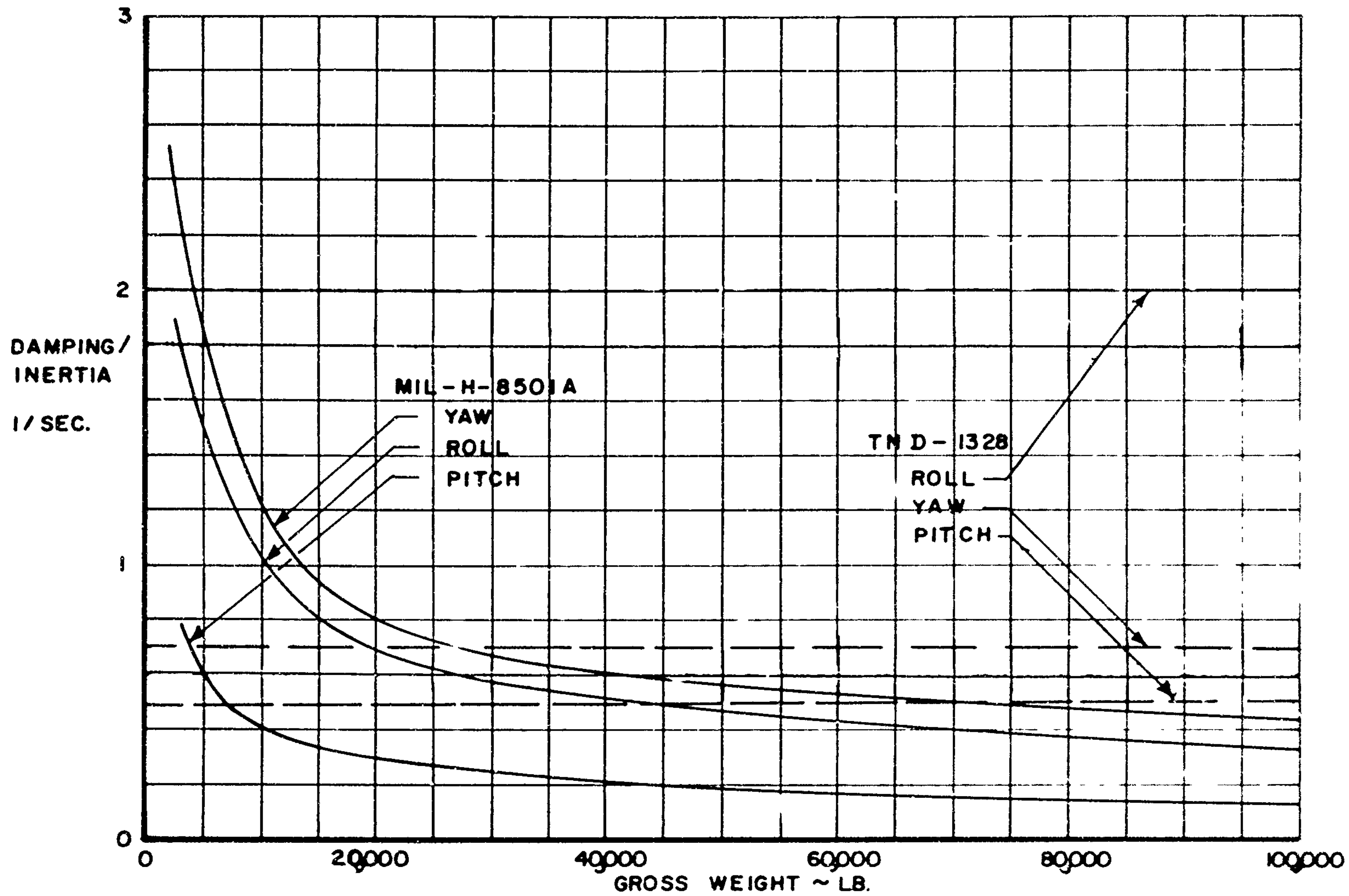


Figure 2 - Damping/Inertia, VFR

respectively. Figures 4 through 9 indicate control power/inertia values computed from References 2, 3, 4, and 5 for maximum control deflection applied to typical VTOL vehicles of various gross weights. Corresponding conditions for Figures 4 through 6 and 7 through 9 are based on zero and 0.2-second system time lag, respectively. Figures 4 and 7 correspond to IFR, 5 and 8 to VFR, and 6 and 9 to emergency conditions. Curves shown in Figures 1 through 9 show only minimum acceptable values except for Reference 4 damping and Reference 5 control power and damping, which represent "desired" characteristics.

Maximum values of control power/inertia are shown for zero time lag in Figures 10 and 11, and for 0.2-second time lag in Figures 12 and 13. IFR conditions are shown in Figures 10 and 12, and VFR and emergency conditions in Figures 11 and 13, with maximum control deflection applied to typical aircraft. Maximum values are not specified for some axes and conditions. It is cautioned that maximum and minimum values of control power/inertia shown in Figures 4 through 13 correspond to minimum or desired damping/inertia values. It is usually necessary to increase the minimum and maximum values of control power/inertia to maintain the same handling qualities rating if larger values than minimum or desired damping/inertia are used. Maximum damping/inertia values are not specified in References 2 through 4. The maximum value of damping/inertia corresponding to the response times given in Reference 5 is 10.0 for each axis. The minimum values are 1.0 for pitch and roll, and 0.667 for yaw.

Damping/inertia and control power/inertia values of Figures 1 through 13 were transformed from requirements of References 2, 3, and 5 as described in Appendix I. Inertia moments used in computing damping/inertia were determined from Appendix II, Figure 23, which is representative of typical VTOL (and non-VTOL vehicles). Control power/inertia values given in Figures 4 through 13 do not include requirements for trim or gyroscopic effects zero and 0.2-second system time lag were used in calculating the control power/inertia from requirements given in terms of specified angular displacements in specified time.

References 2 through 5 include only the portion of control power concerned with maneuvers. Additional control power must be provided as necessary to maintain trim or force and moment equilibrium as required by characteristics peculiar to the vehicle. Control power essential to the minimization of motion caused by disturbances may be included in the requirements; however, separate analyses should be made of control power required for maneuvering and the control power required to handle disturbances. The larger of the two is then used.

Additional recommendations regarding handling qualities, less formal than References 2, 3, 4, and 5, have been proposed. Reference 2 is reviewed

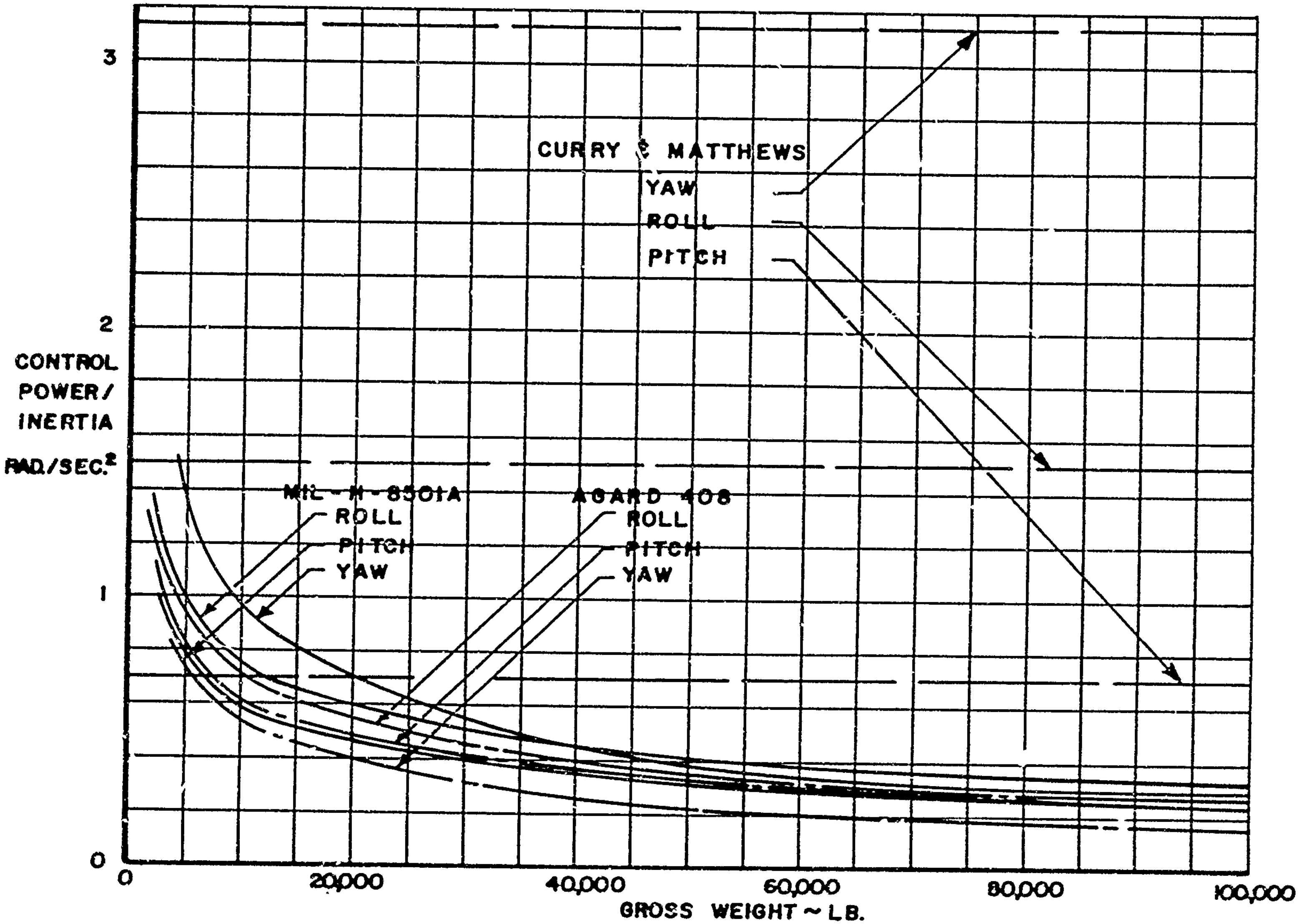


Figure 4 - Control Power/Inertia, IFR, Zero Syster Time Lag

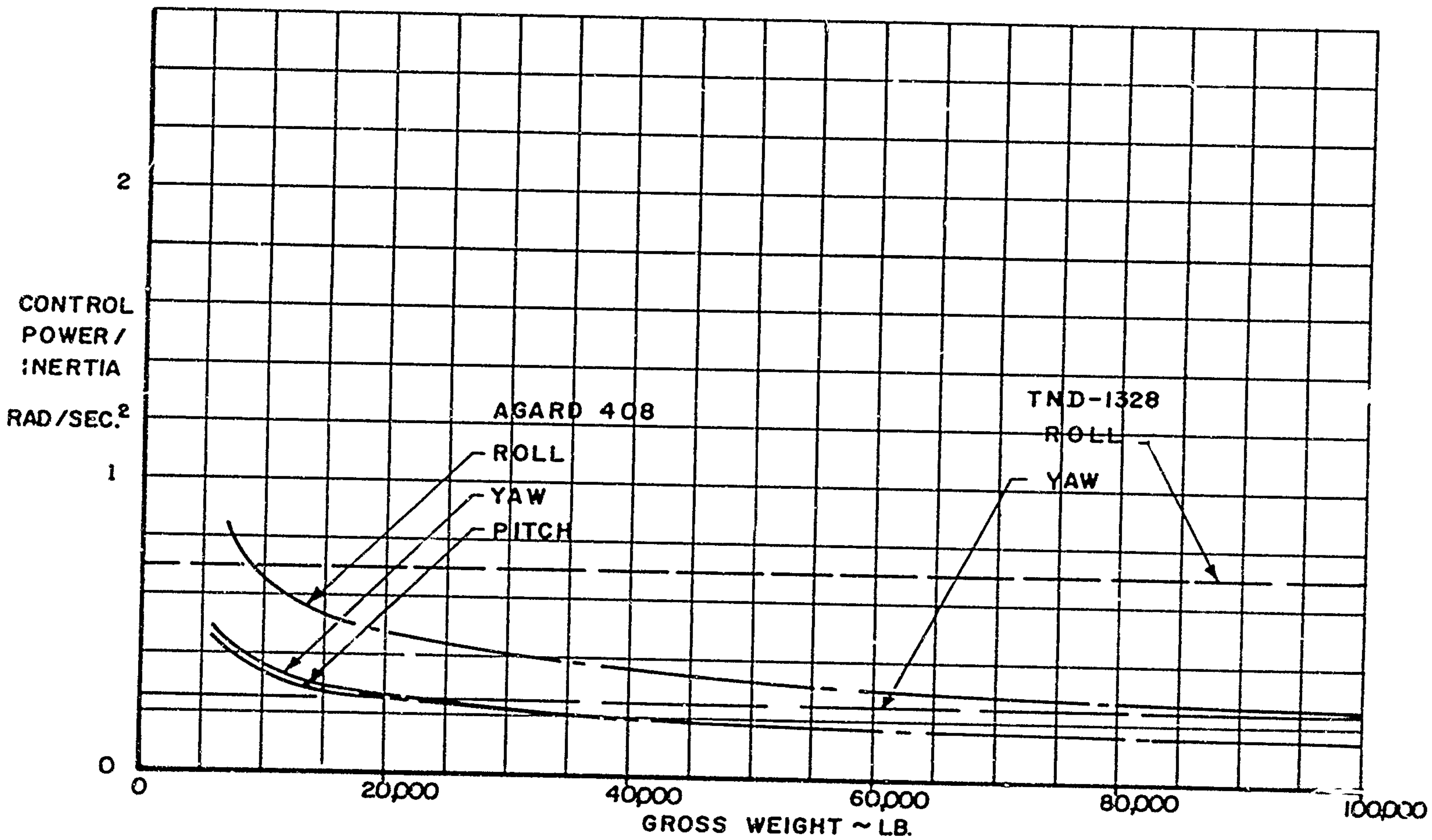


Figure 6 - Control Power/Inertia, Emergency, Zero System Time Lag

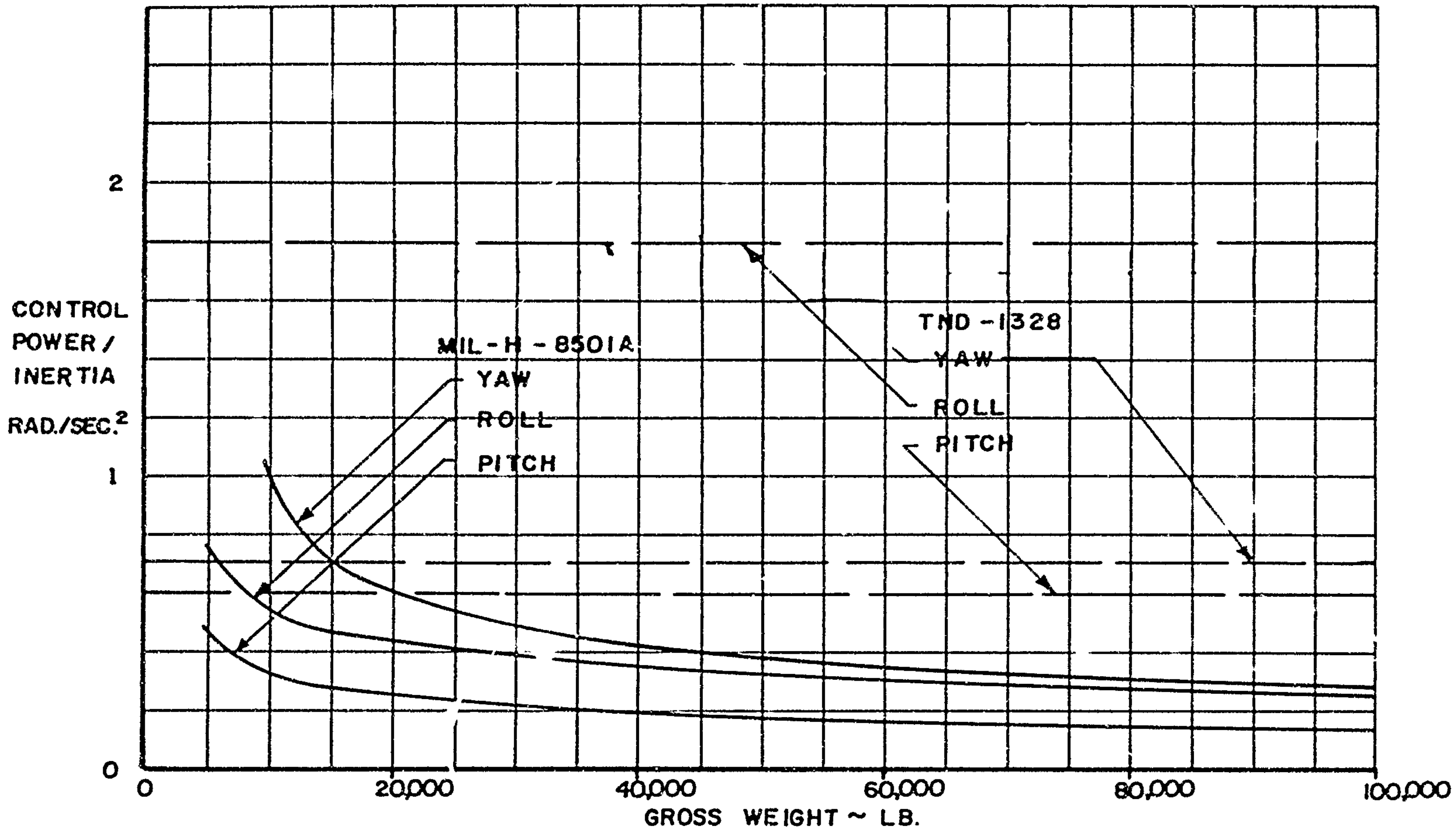


Figure 5 - Control Power/Inertia, VFR, Zero System Time Lag

Figure 7 - Control Power/Inertia, IFR, 0.2 Second System Time Lag

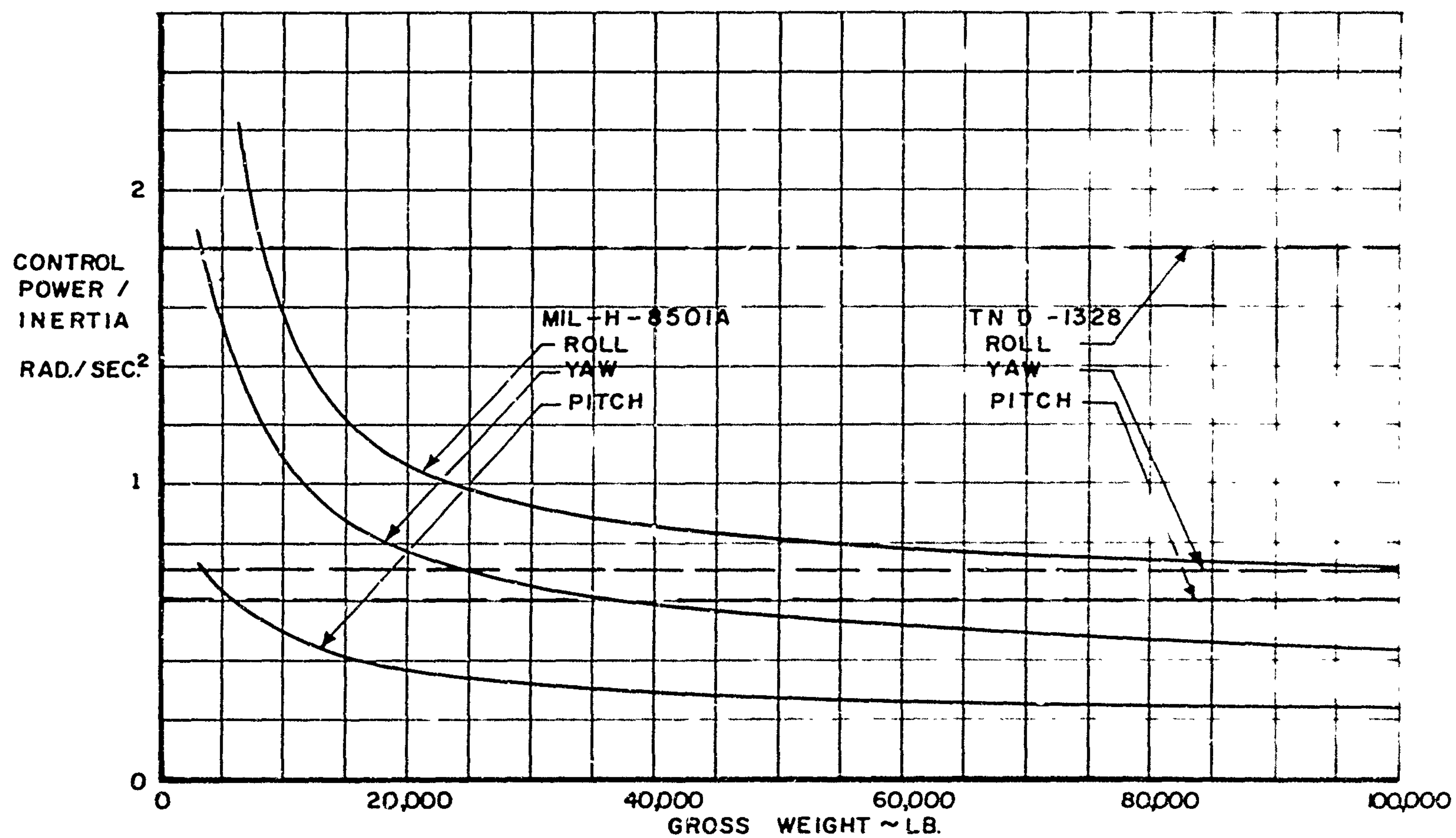


Figure 8 - Control Power/Inertia, VFR, 0.2 Second System Time Lag

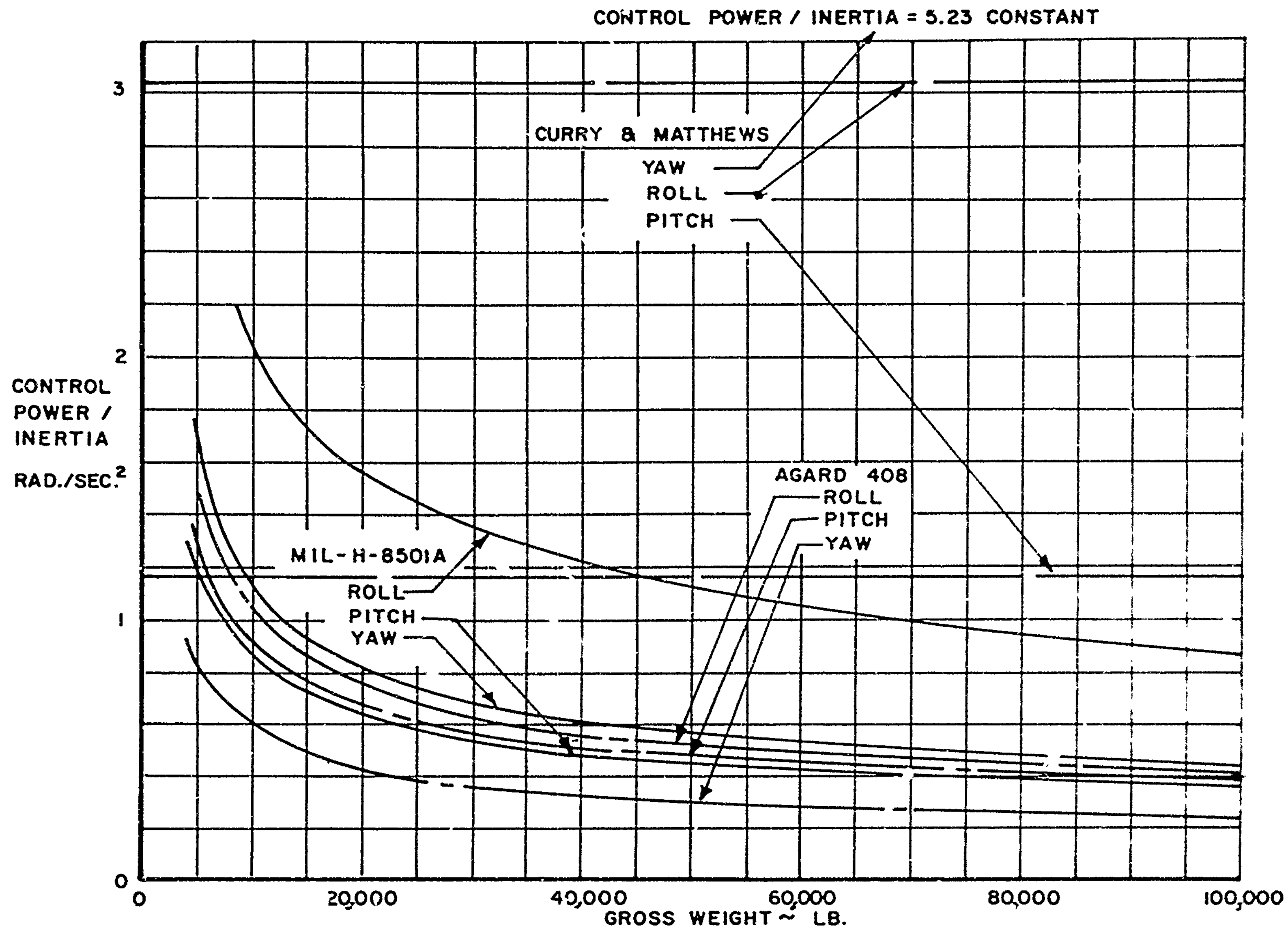


Figure 7 - Control Power/Inertia, IFR, 0.2 Second System Time Lag

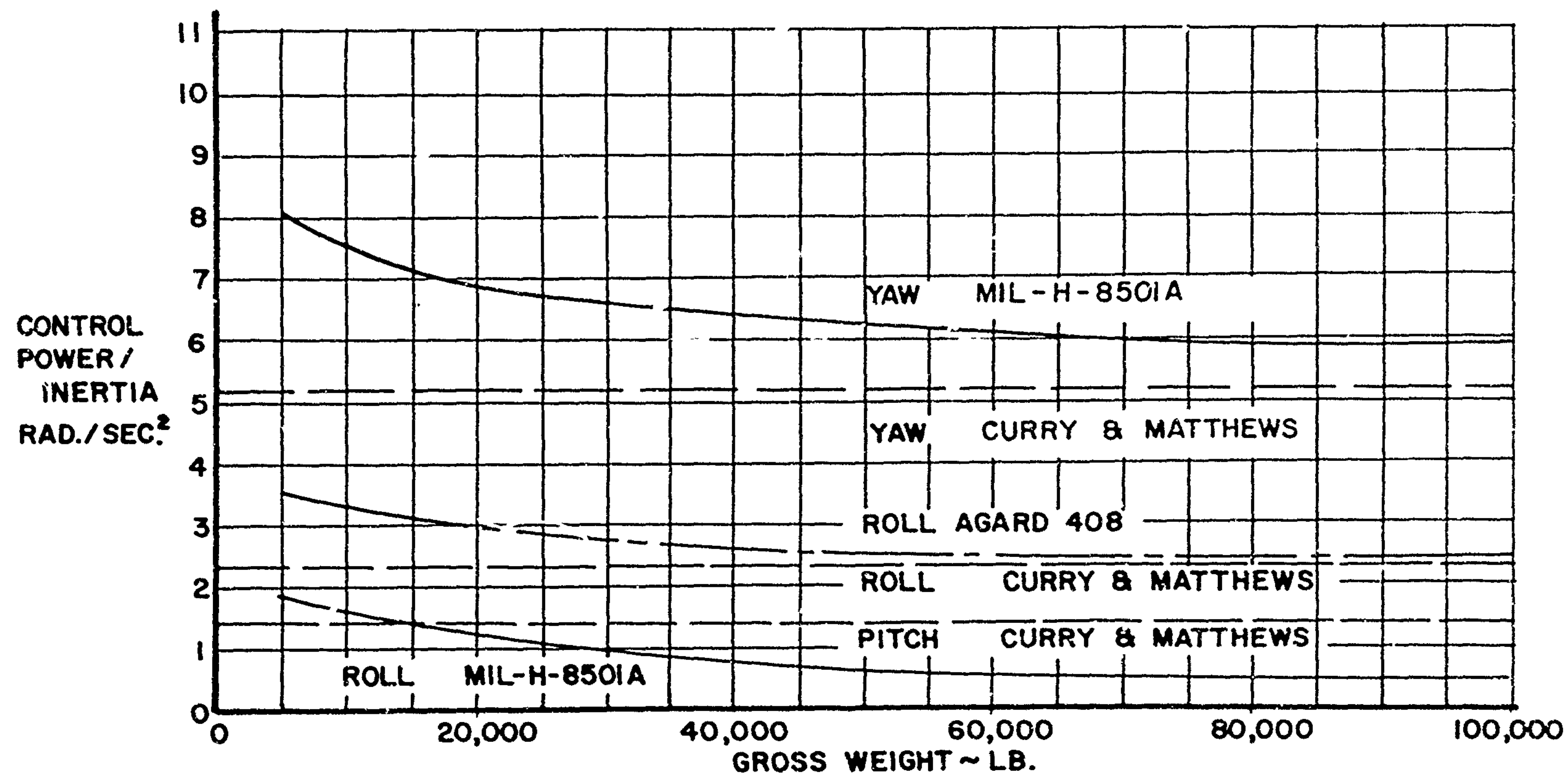


Figure 10 - Maximum Control Power/Inertia, IFR, Zero System Time Lag

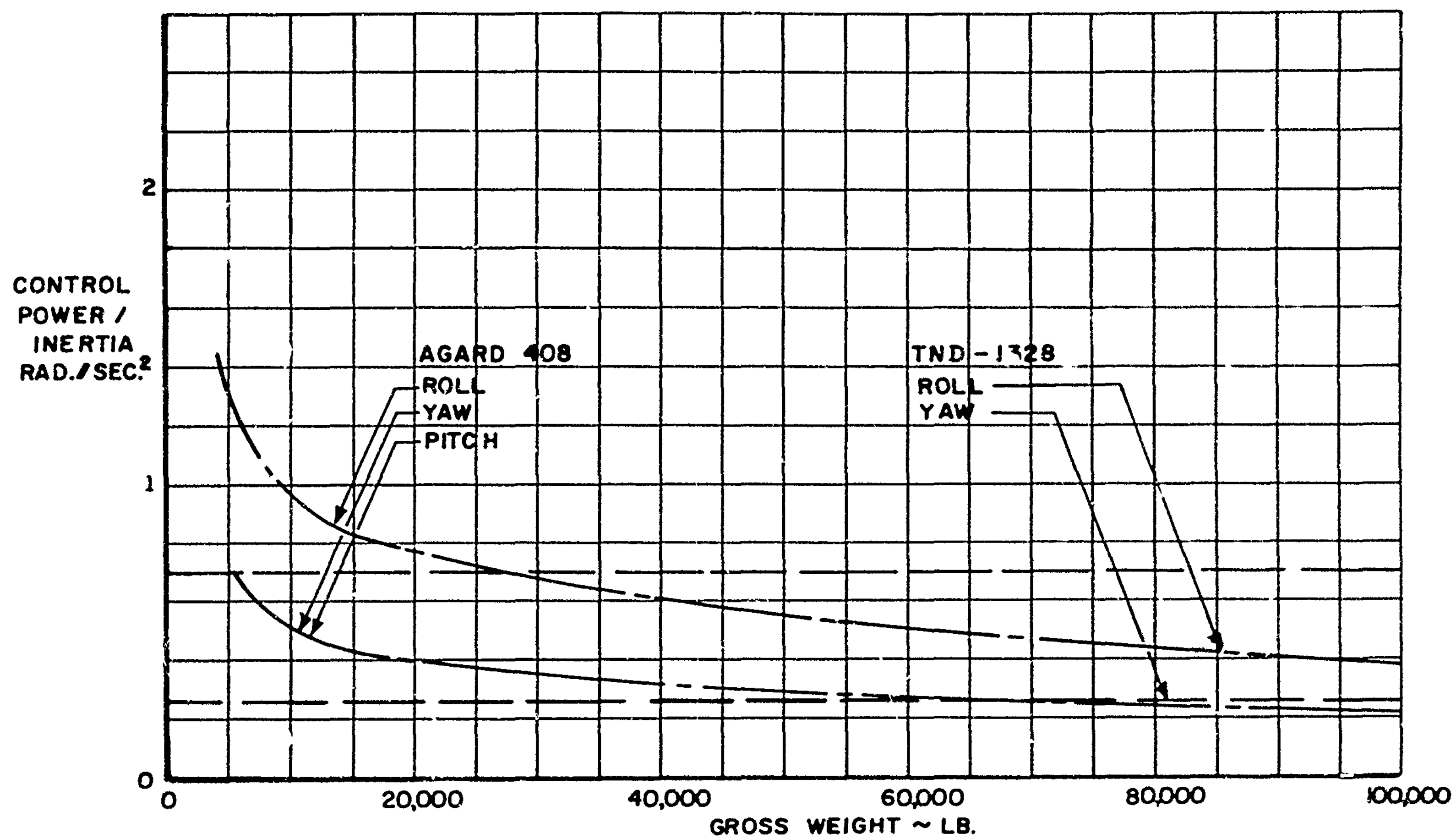


Figure 9 - Control Power/Inertia, Emergency, 0.2 Second System Time Lag

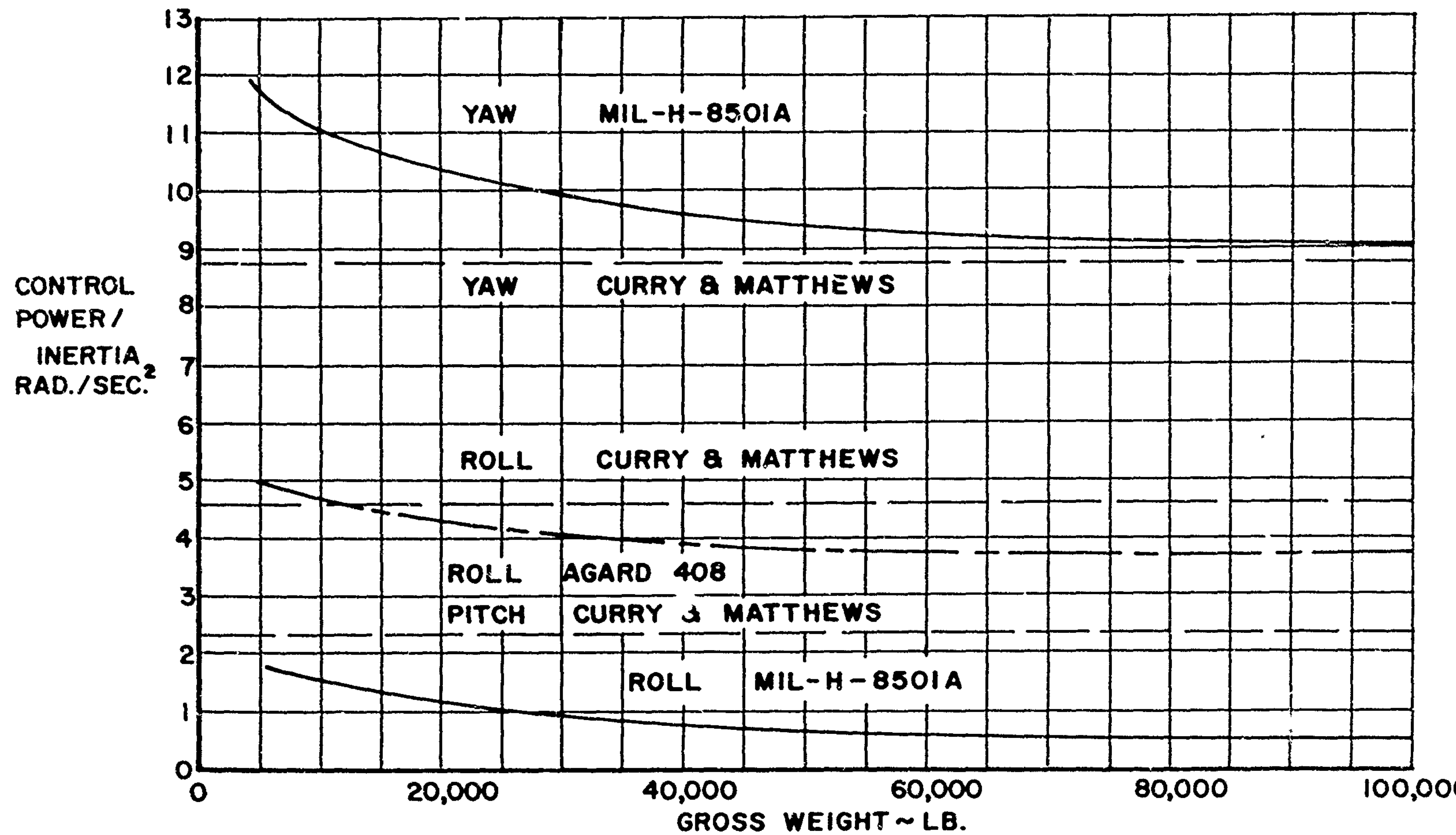


Figure 12 - Maximum Control Power/Inertia, IFR, 0.2 Second System Time Lag

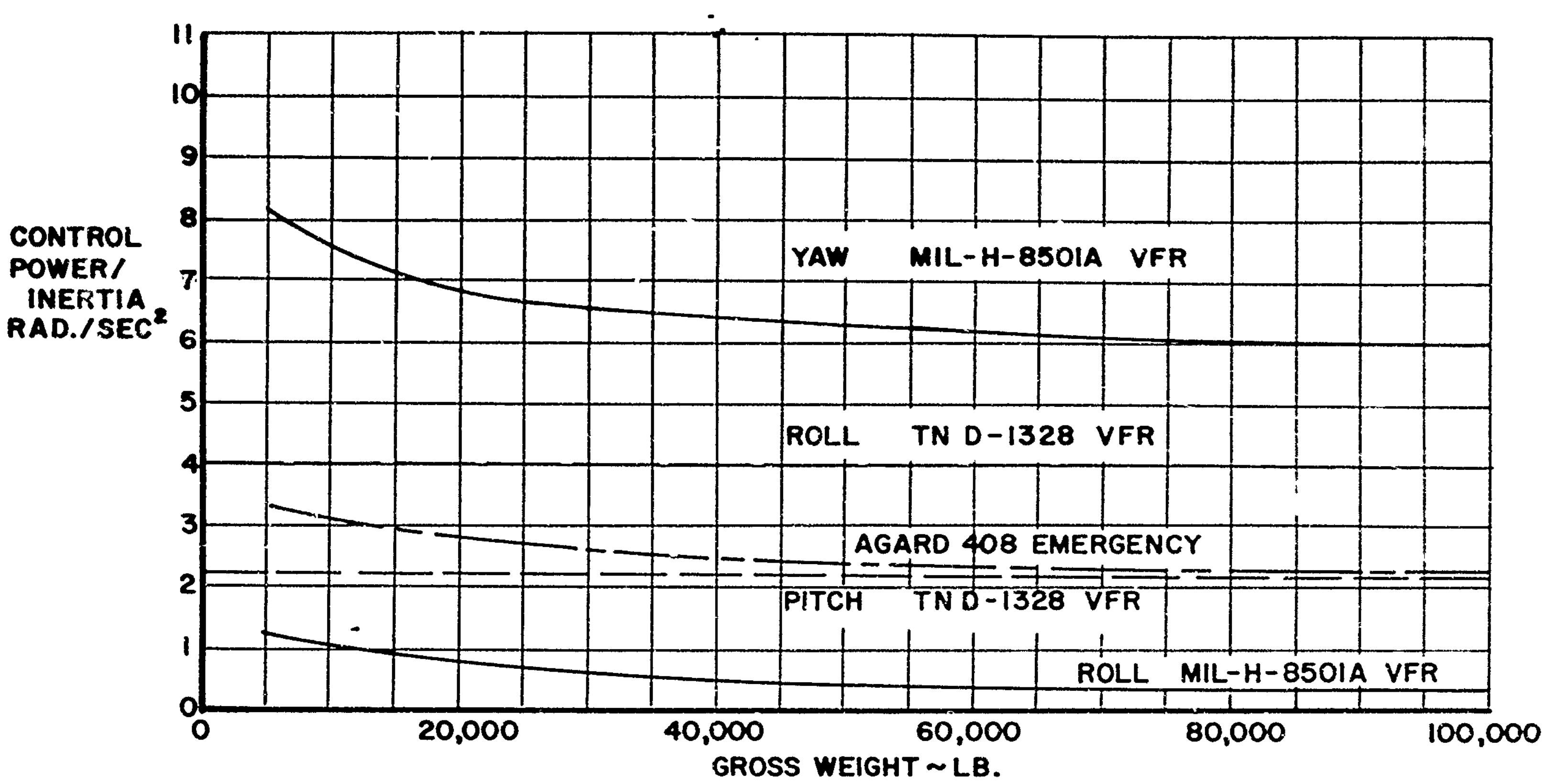


Figure 11 - Maximum Control Power/Inertia, VFR & Emergency Zero System Time Lag

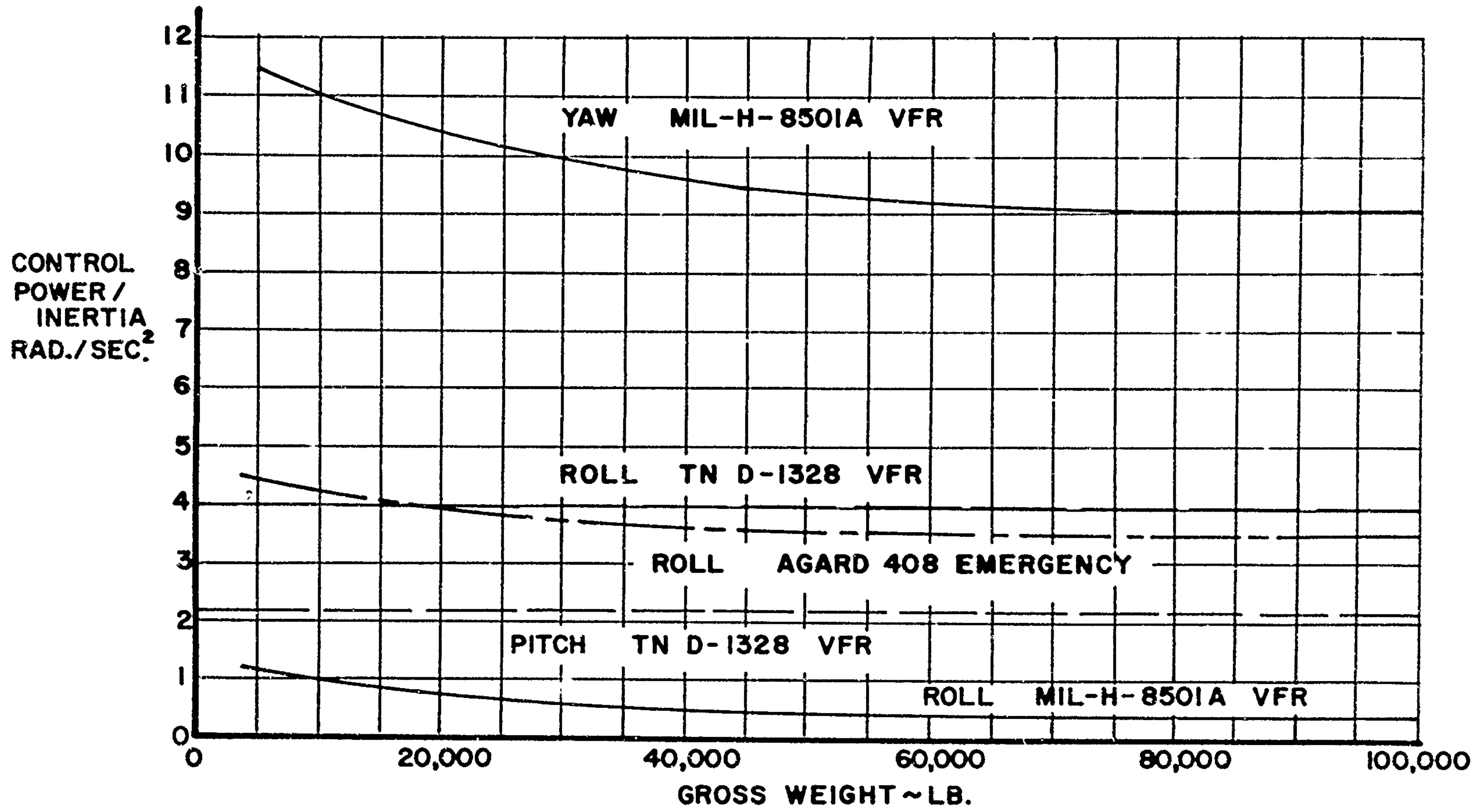


Figure 13 - Maximum Control Power/Inertia, VFR & Emergency 0.2 Second System Time Lag

in References 7 and 8 with consideration of requirements for weapons helicopters. Reference 7 suggests review of stability and control requirements obtained from extreme maneuvers and the specification of maneuver load factor criteria. It is believed that such material would be handled more appropriately as special requirements specified by the procuring agency.

Reference 8 recommends normal accelerations and minimum angular rate criteria for armed helicopters in nap-of-the-earth operation. The minimum angular rates specified are in excess of maximum angular rates measured in nap-of-the-earth flight tests in order to allow for unexpected situations. If limited control travels are used with linear characteristics, oversensitivity may result as compared to maximum angular rates per inch of Reference 2. Further study is indicated.

Reference 9 indicates that current handling qualities criteria are topically adequate but require more effort in quantifying requirements. This report also points out the need for caution in application of some requirements and full consideration of underlying factors in interpretation.

Reference 10 reviews the state of the art with respect to instrument flight operation. This document indicates that instrument flight with helicopters at the current stage of investigations is feasible for descent angles of less than 12 degrees and for speeds of more than 25 knots. Further development including inventions of greatly improved instrument display systems and radical betterment of flying qualities (including reduction of inherent instabilities such as the vortex ring state encountered in moderate descent rates near zero forward speed) is essential to near vertical descents during minimum visibility conditions. Criteria for instrument flight with other VTOL types are not available.

A comprehensive review was made of Reference 3 by the AGARD Technical Assistance Group, Reference 11. Differences in desired damping/inertia and control power/inertia values computed from Reference 3 and desired values obtained from flight tests of the X-14A and P-1127 aircraft are presented. Many other items are included in the recommendations.

Nearly all of the work on VTOL handling qualities, including current specifications, Reference 2, 3, 4, and 5, is based on vehicle systems in which the control power is proportional to control displacement and the damping is proportional to angular velocity. Although some work has been done with vehicles having more sophisticated systems, such as devices which provide vehicle angular displacement as a function of control movement and damping related to acceleration, these systems are considered beyond the scope of this investigation.

This paper is intended to be a broad fundamental study aimed primarily at effects of size, but necessarily including some studies of pilot-vehicle relationships. It is not intended to arrive at definite values, but to study means of accounting for vehicle differences from criteria obtained for specific vehicles. The approach taken is to review first the variation of inherent capabilities of both jet and helicopter VTOL vehicles with size, then to study how these fit both the pilot and the mission.

EFFECT OF SIZE ON FLIGHT HANDLING CAPABILITY

The basic handling qualities characteristics to be considered are:

Linear acceleration, $\ddot{x}$, $\ddot{y}$, $\ddot{z}$ (equal to force/mass, F/m, feet/seconds^2).

Linear rate damping/mass, F_v/m, (1/seconds).

Angular acceleration, $\ddot{\theta}$, $\ddot{\phi}$, $\ddot{\psi}$, (equal to the control power/inertia, M_c/I, radians/second^2).

Angular rate damping/inertia, C/I, (1/seconds).

Angular rate time constant, I/C, (time to obtain 63 percent of the final angular rate, seconds). This is the reciprocal of the damping/inertia.

Final angular rate, M_c/C, (radians/second).

The various handling qualities criteria are stated in terms of one or more of the above characteristics. Such factors as natural frequency occurring in the pilot's frequency band or time lags in control response of the vehicle are properties of a particular design, and the variation with size can also be handled by the similitude approach.

To determine the inherent variation of these two basic handling qualities characteristics with vehicle size it is first necessary to state the basic characteristic associated with size variation: that is, vehicle weight is generally proportional to the cube of a characteristic dimension, as shown in Appendix II, Figures 17 and 18:

$$W \sim L^3.$$

This is a statement that the vehicle densities are relatively invariant. An associated statement is that the wing loading or disc loading tends to increase with size, Appendix II, Figure 22:

$$\frac{W}{L^2} \sim L.$$

This is the variation that satisfies the ancient square-cube law while achieving operationally feasible vehicles of large size. Vehicles of

given planform family will generally follow these relations. The constant of proportionality will vary for radical changes in planform.

The vehicle inertia is $I \sim WL^2$, where L is the characteristic dimension appropriate to the axis about which the inertia is computed. Inasmuch as $W \sim L^3$, this leads to $I \sim L^5$, which is essentially in agreement with Appendix II, Figure 23.

It is recognized that vehicles can have significantly different variations of weight and moments of inertia with the major dimensions, particularly for special purpose vehicles. Other characteristics too may not closely fit assumed functions of size. In general such deviations merely change constants or proportionality and the trends will be only slightly affected.

JET VTOL

Control Power

The linear acceleration of VTOL vehicles is controlled by variation or tilting of the propulsive thrust. The propulsive thrust obviously must be larger than the weight of the vehicle in order to permit upward acceleration and to allow horizontal acceleration without downward acceleration. The acceleration is equal to the force/mass which tends to be constant for vehicles of the same type.

$$\ddot{x},\ \ddot{y},\ \ddot{z} \sim F_c/m \sim \text{constant (i.e., independent of size).}$$

The angular control power of jet lift VTOL is obtained from thrust modulation for engines mounted near the extremities or from bleed air nozzles at the extremities for engines mounted near the center. In either case the force for control is obtained by increasing the equivalent installed thrust over that required for lift. If the force available for control is a given percentage of the installed thrust, T, and $T \sim W$, then

$$M_c \sim TL \sim WL \sim L^4$$

and

$$\frac{M_c}{I} \sim \frac{L^4}{L^5} \sim \frac{1}{L} \, .$$

This result indicates that the control power/inertia ratio tends to decrease with increasing size, or conversely, that increasingly higher percentages of the installed power must be diverted to the controls if a constant control power/inertia is required. The consequent effect of reduction in control power/inertia with increasing size is discussed under the heading PILOT-VEHICLE COMPATIBILITY and in Appendix IV.

Representative values of control power/inertia for X-14A jet VTOL research aircraft (Reference 4) are 0.6, 1.8, and 0.5 radian per second squared for pitch, roll, and yaw, respectively.

Damping and Response Time

The rate damping of the linear motions of jet VTOL aircraft is attributed to the change of momentum of the jets and to the aerodynamic drag with velocity:

Vertical Damping,

$$C_V = dF_V/dV_V = d\left[m_j(V_j - V_V) - \rho V_V^2\, SC_{D_V}/2\right]/dV_V = -m_j - \rho V_V SC_{D_V}$$

$$T = m_j\,(V_j - V_V) = W$$

$$C_V/m = \left[-W/(V_j - V_V) - \rho V_V SC_{D_V}\right]/(W/g)$$

$$C_V/m = -g/(V_j - V_V) - g\, \rho V_V SC_{D_V}/W$$

$$C_V/m \sim K + 1/L$$

$$C_V/m = -g/V_j \text{ for hover } (V_V \approx 0).$$

Horizontal Damping,

$$C_H = dF_H/dV_H = d\left[-m_j V_H - \rho V_H^2\, SC_D/2\right]/dV_H = -m_j - \rho V_H SC_D$$

$$C_H/m = -g/(V_j - V_V) - g\, \rho V_H SC_D/W$$

$$C_H/m \sim K + 1/L$$

$$C_H/m = -g/V_j \text{ for hover.}$$

The response times for the linear motions are then:

Vertical Translations,

$$\tau_V = m/C_V = W(V_j - V_V)/g\left[W + \rho V_V SC_{D_V}\,(V_j - V_V)\right]$$

$$\tau_V \sim 1/(K + 1/L)$$

$$\tau_V = V_j/g \text{ for hover.}$$

Horizontal Translation,

$$\tau_H = W(V_j - V_V)/g\left[W + \rho V_H SC_D\,(V_j - V_H)\right]$$

$$\tau_H \sim 1/(K + 1/L)$$

$$\tau_H = V_j/g \text{ for hover.}$$

Exhaust velocities range from 500 feet per second for a representative fan to above 2000 feet per second for a pure jet. The corresponding damping range is -0.064 to -0.016 per second and the response time varies from 15.6 to 62.1 seconds.

Since the aerodynamic angular rate damping of a hovering jet VTOL is negligible, the force for damping must also be supplied from the engines. If the forces available for damping are a given percentage of the installed thrust,

$$C = \frac{M}{\dot{\theta}} \sim \frac{TL}{\dot{\theta}} \sim L^4$$

and

$$\frac{C}{I} \sim \frac{L^4}{L^5} \sim \frac{1}{L}.$$

This result indicates that the damping/inertia tends to decrease with increasing size unless the force available for damping, i.e., the installed thrust, is increased. Typical damping/inertia values for the X-14A jet VTOL research vehicle (Reference 4) are -0.5, -2.0, and -0.7 per second for pitch, roll, and yaw, respectively.

The response time to reach 63% of final angular rate is the reciprocal of the damping/inertia,

$$\tau = I/C \sim L.$$

Typical angular response times for X-14A are 2.0, 0.5, and 1.4 seconds for pitch, roll, and yaw, respectively.

Angular Rate

The final angular rate is $\dot{\theta} = \frac{M_C}{I} \Big/ \frac{C}{I} \sim \frac{1}{L} \Big/ \frac{1}{L} \sim \text{constant}.$

That is, if fixed percentages of the installed thrust are diverted to control power and to damping, the final angular rate is independent of size. Note that if the fraction diverted to control power is greater than the fraction diverted to damping, the final angular rate is indefinitely high. Similarly, a response time constant I/C can only be specified for rates at which the control input does not over-saturate the damping system.

HELICOPTERS

In addition to the basic assumption that the disk loading is proportional to size ($W \sim L^3$), relations are shown in the following for helicopters wherein the disk loading is constant, independent of size ($W \sim L^2$). It

is also considered that the tip speed (ΩR) will be constant because of Mach limitations. The blade lift coefficient for optimum design is independent of size, therefore the blade loading (W/bcR) is assumed to be constant. The following discussion concerns both the articulated and rigid rotor and gyro stabilization.

Translation Characteristics - Control Power

The control power for producing acceleration for horizontal or vertical translation of the helicopter near hover is derived as follows for a function of collective pitch. The analysis is based on a constant chord, ideally twisted blade; however, the effects on size will be similar for moderate variations of blade geometry, Reference 12, pages 58 and 60:

$$T = (\rho/4)\,(\Omega R)^2\, abcR(\theta_t - v/\Omega R) = 2\rho A v^2 = W$$

$$dT/dv = 4\rho Av,\quad \Omega R = \text{constant},\quad W/bcR = \text{constant}$$

$$F_c = dT/d\theta_t = d\left[(\rho/4)(\Omega R)^2\, abcR(\theta_t - v/\Omega R)\right]/d\theta_t$$

$$F_c = (\rho/4)\,(\Omega R)^2\, abcR/\left[1 + (1/16)\ \Omega\, RabcR/A(W/2\rho A)^{1/2}\right].$$

For the control power/mass,

$$F_c/m = 2\,g/\left[(8\,W/\Omega\, RabcR) + (W/2\rho A)^{1/2}\right]$$

$$F_c/m \sim 1/(K_1 + W^{1/2}/L);$$

for disk loading proportional to size ($W \sim L^3$),

$$F_c/m \sim 1/(K_1 + L^{1/2});$$

for constant disk loading ($W \sim L^2$),

$$F_c/m = \text{constant}.$$

Short-time vertical acceleration increments of 1g to 1.5g, converting some rotor energy to lift, are available in helicopters in the 4000-pound class. This tends to decrease slowly with increasing disk loading.

Translation Characteristics - Damping and Response Time

The vertical damping/mass and response are derived as follows as a function of vertical velocity. The analysis is based on a constant chord, ideally twisted blade, Reference 12, page 129:

$$T = (\rho/4)\,(\Omega R)^2\, abcR\left[\theta_t - v/\Omega R - V_V/\Omega R\right] = W$$

$$T = 2\rho A(v^2 + V_V v),\quad dv/dV_V = \left[(dT/dV_V 2\rho A) - v\right]/(2v + V_V)$$

$$C_V/m = gdT/dV_VW = -(\rho/4)\Omega\,RabcR(1 + dv/dV_V)$$

$$C_V/m = \frac{-g(\rho/4)\Omega\,RabcR\,[2\rho\,Av + 2\rho\,AV_V]}{[4\rho\,Av + 2\rho\,AV_V + (\rho/4)\Omega\,RabcR]\,W}$$

$$C_V/m = -g/[8W/\rho\Omega\,RabcR + (W/2\rho\,A)^{1/2}]\ \text{as}\ V_V \rightarrow o$$

$$C_V/m \sim -1/(K_1 + W^{1/2}/L),$$

then for

Disk loading proportional to size,

$$C_V/m \sim -1/(K_1 + L^{1/2}),\ \tau_V \sim K_1 + L^{1/2};$$

Constant disk loading,

$$C_V/m = \text{constant},\ \tau_V \sim \text{constant}.$$

That is, the vertical damping/mass is independent of size for constant disk loading, and decreases slowly with size if the disk loading is increasing. The vertical damping/mass for a typical 4000-pound helicopter is -0.5 per second.

The rotor damping in horizontal translation is obtained from the equation for the horizontal force H (Reference 12, p. 198).

$$H = (\rho/4)(\Omega\dot{R})^2\,abcR\left(\frac{\delta\mu}{a} + \frac{2\theta a_1}{3} + \mu\lambda\theta + \frac{3\lambda a_1}{2} + \frac{\mu a_1^{\,2}}{2} - \frac{a_o b_1}{3} + \frac{\mu a_o^{\,2}}{2}\right)$$

where a_1 and b_1 are negligible near hover, θ is constant, and

$$v = (W/2\rho\ A)^{1/2}\ \text{near hover.}$$

Horizontal damping/mass and response time are:

$$C_H/m = -gdH/dV_HW = -gdH/d\mu\,\Omega\ \ RW$$

$$C_H/m = -g(\rho/4)\ (\Omega R)abcR\left(\frac{\delta}{a} + \lambda\theta + \frac{a_o^{\,2}}{2}\right)/W$$

Where $\theta = \alpha_b + \lambda$ and $a_o = \beta_o \sim WR/W(\Omega R)^2 \sim L$ (Reference 12, pages 141-143) for near hovering,

$$C_H/m \sim -(K_2 + K_4W^{1/2}/L + K_5W/L^2 + L^2)$$

$$\tau_H \sim 1/(K_3 + K_4W^{1/2}/L + K_5W/L^2 + L^2);$$

Disk loading proportional to size,

$$C_H/m \sim -(K_3 + K_4 L^{1/2} + K_5 L + L^2) \; [illegible] \; + K_4 L^{1/2} + K_5 L + L^2);$$

Disk loading constant,

$$C_H/m \sim -(K_3 + K_4 \cdot K_5 + L^2) \; [illegible] \; 3 \; [illegible] \; + L^2).$$

The typical helicopter translationa[illegible]/mass is about -0.01 per second for horizontal motions. The hor[illegible]l damping increases rapidly with size for helicopters.

<u>Yaw - Control Power</u>

The yaw control power/inertia of a tail rotor helicopter in hovering is ($l_T \sim L$):

$$M_c/I = l_T(dT/d\theta_t)/I$$

$$M_c/I \sim L/(K_6 + W^{1/2}/L)L^2$$

$$M_c/I \sim 1/(K_6 L + W^{1/2}) \; ,$$

For disk loading proportional to size ($W \sim L^3$),

$$M_c/I \sim I/(K_6 L + L^{3/2});$$

For constant disk loading ($W \sim L^2$),

$$M_c/I \sim 1/L.$$

The control power/inertia decreases rapidly with size.

<u>Yaw - Damping and Response Time</u>

The yaw damping/inertia and response time are:

$$C/I = l_T(dT/d\dot{\psi})/I = l_T(dT/dV)(dV/d\dot{\psi})/I = l^2_T(dT/dV)/I$$

where $V = l_T\dot{\psi}$ and $dV/d\dot{\psi} = l_T$.

From the previous dT/dV_V,

$$C/I \sim -L^2/(K_6 + W^{1/2}/L)L^2 \sim -1/(K_6 + W^{1/2}/L);$$

Disk loading proportional to size,

$$C/I \sim -1/(K_6 + L^{1/2}), \quad \tau \sim K_6 + L^{1/2};$$

Disk loading constant,

$$\dot{C}/I = \text{constant}, \ \tau = \text{constant}.$$

Yaw - Angular Rate

The final angular rate of yaw is:

$$\dot{\psi} = M_c/C \sim (K_6 + W^{1/2}/L)/(K_6 L + W^{1/2}) \sim \frac{1}{L}$$

The final angular rate decreases with size for either disk loading:

$$\dot{\psi} \sim 1/L.$$

The yaw control power/inertia, damping/inertia, and response time for a typical 4000-pound helicopter (without auxiliary damping) are 2.2 radians per second squared, 1.08 per second and 0.93 second, respectively. A yaw control power/inertia for yaw rate and response time recommended in Reference 5 is 3.14 radians per second squared. A yaw response time of 0.5 second is recommended in Reference 5, indicating a need for auxiliary damping if precise control is desired.

Pitch & Roll - Control Power, Articulated Rotor With Offset Flapping Hinge

The control power of the articulated rotor in pitch or roll is:

$$M_c = Th\theta_R + (W_R/2g)\ R\ \bar{R}\ \ \Omega^2\ (e/R)\ \theta_R\ ,$$

with $T = W$, $h \sim L$, $\dot{\theta}_R$ = constant, $W_R \sim W$, $\bar{R} \sim R \sim L$, ΩR = constant, $e \sim R$, and $I \sim WL^2$; then

$$M_c/I \sim 1/L + K_8/L^2 \qquad \text{for } W \sim L^2 \text{ or } W \sim L^3, \text{ independent}$$

of disk loading. The control power/inertia will decrease with increasing size unless the rotor height or hinge offset is increased disporportionately to the size.

Pitch & Roll - Control Power, Rigid Rotor

The control power of the rigid rotor per unit of feathering angle is:

$$M_c = TH\theta_c + K_\beta \theta_c.$$

The rotor stiffness may be stated in terms of an equivalent flapping hinge offset e:

$$K_\beta = \frac{W_R \bar{R}}{2g} \; \Omega^2 \; e = \frac{W_R}{2g} R \bar{R} \; \Omega^2 \frac{e}{R} \; .$$

Assuming W_R/W = constant, $\bar{R}/R$ = constant, $\Omega^2 R^2$ - constant and e/R = constant,

$$K_\beta \sim W \sim L^3, \; I \sim WL^2$$

and $\dfrac{M_c}{I} = \dfrac{Th\theta_c + K_\beta \theta_c}{I} \sim \dfrac{WL + WK_1}{WL^2} \sim \dfrac{1}{L} + \dfrac{K_8}{L^2}$

where K_8 is a constant, independent of disk loading ($W \sim L^3$ or $W \sim L^2$), but proportional to the equivalent hinge offset ratio.

The general form of the control power/inertia relation is the same for both rigid rotors and articulated rotors having offset flapping hinges; in practice, however, the rigid rotor obtains large equivalent hinge offsets more easily than the flapping rotor.

<u>Pitch & Roll - Damping and Response Time, Articulated Rotor Without Hinge Offset</u>

In the simple articulated rotor, damping of body motions arises from the rotor lag in following body angular rates. The damping moment is:

$$M_d = TH \, \Delta \, \theta_R .$$

The lag $\Delta\theta_R$ is that required to precess the rotor by aerodynamic moments to follow the body-shaft angular rates:

$$\Delta\theta_R = \frac{J_R \Omega \dot{\theta}}{M_A}$$

where aerodynamic precessing moment per unit of feathering angle

$$M_A \sim b \;\; \Omega^2 \; R^4 \; c \; \sim \; (bcR) \; (\Omega^2 R^2) R,$$

but

$$bcR \sim W \text{ (Blade loading constant)},$$

$$\Omega^2 R^2 = \text{constant (Tip speed constant)};$$

therefore, $M_A \sim WR \sim WL$.

Assuming that the rotor weight is a nearly invariant fraction of the gross weight, the rotor polar moment of inertia is:

$$J_R \sim WR^2 \sim WL^2$$

$$J_R\Omega \sim WL^2/L \sim WL$$

and

$$\frac{\Delta\theta_R}{\dot{\theta}} \sim \frac{J_R\Omega}{M_A} \sim \frac{WL}{WL} = \text{constant};$$

therefore,

$$\frac{C}{I} \sim \frac{M_d}{\dot{\theta}I} \sim \frac{WL}{WL^2} \sim \frac{1}{L} \cdot$$

The response time

$$\tau = \frac{I}{C} \sim L.$$

That is, the damping/inertia decreases with increasing size, and the characteristic response time increases with increasing size.

Pitch and Roll - Damping and Response Time, Rigid Rotor or Offset Hinge Articulated Rotor

For the rotor without stabilizing gyroscope, damping of body motions, like that of the simple articulated rotor, arises from the rotor lag in following angular rates:

$$M_d = Th\,\Delta\theta_R + K_\beta\,\Delta\theta_R, \text{ or } M_d = Th\,\Delta\theta_R + \frac{W_R}{2g} R\bar{R}\Omega^2 \frac{e}{R}\;\Delta\theta_R \cdot$$

As for the simple articulated rotor, $\Delta\theta_R/\dot{\theta}$ is also invariant with size in the rigid or offset-hinge articulated rotor without control gyro. Therefore,

$$C = \frac{M_d}{\dot{\theta}} \sim Th + K_\beta, \text{ or } C = Th + \frac{W_R}{2g} R\bar{R}\Omega^2 \frac{e}{R}$$

and $$C/I \sim \frac{Th + K_\beta}{I} \sim \frac{WL + WK_8}{WL^2} \sim \frac{1}{L} + \frac{K_8}{L^2},$$

independent of disk loading and where K_8 is a constant. Inasmuch as the control power and the damping vary in the same manner, the final angular rate is invariant with size. The response time

$$\tau = I/C \sim \frac{L^2}{L + K_8} \cdot$$

That is, the damping/inertia decreases with increasing size and the response time increases with increasing size. These variations with size

are more rapid where large equivalent hinge offsets are used. However, the use of equivalent hinge offsets provides significantly more damping or lower response time within the foreseeable range of helicopter size.

Pitch & Roll - Damping and Response Time With Control Gyro

For the rigid rotor with control gyro, the damping is determined by the lag in control gyro attitude behind the body and shaft attitude. If the precessional moment on the control gyro is proportional to the moment $\dot{M}$ on the main rotor, $M = K_\beta \, \Delta\theta_R$, and $M \sim M_G = J_G \, \Omega\dot{\theta}$,

$$\Delta\theta_R \sim \frac{J_G \Omega\dot{\theta}}{K_\beta} \sim \frac{WL}{WK_8} \sim \frac{L}{K_8} \text{ (assuming } J_G \sim J_R \sim WL^2\text{)},$$

then

$$\frac{C}{I} = \frac{M_d}{\dot{\theta} I} \sim \frac{Th\,\Delta\theta_R + K_\beta\,\Delta\theta_R}{\dot{\theta} I} \sim \frac{WL^2/K_8 + WL}{WL^2} \sim \frac{1}{K_8} + \frac{1}{L},$$

independent of disk loading and where K_8 is a constant.

The response time

$$\tau = I/C \sim \frac{K_8 L}{L+K_8}.$$

That is, the damping/inertia will tend to decrease and the response time to increase as the size is increased when a control gyro is incorporated with the rigid rotor. From this it may also be seen that within reasonable limits the use of the control gyro and rigid rotor or hinge offset allows the damping and response time to be tailored arbitrarily.

Pitch & Roll - Angular Rate

For either the rigid or articulated rotor, the steady angular rate per unit of feathering angle is:

$$\frac{\dot{\theta}}{\theta_c} \sim \frac{M_A}{J_R \Omega}.$$

It has been shown that

$$M_A \sim LW$$

$$J_R \Omega \sim LW;$$

therefore,

$$\dot{\theta} = \frac{M_A\,\theta_C}{J_R\,\Omega} \sim \frac{LW}{LW} = \text{constant and independent of disk loading.}$$

Thus the angular rate obtainable is invariant with size, although it has previously been shown that the characteristic time to reach the angular rate increases with size.

Pitch & Roll - Relative Magnitude of Equivalent Hinge Offset Terms

In the foregoing discussions of control power and damping, the terms involving the constant K_8 are associated with the equivalent hinge offset e/R, and the other terms are associated with the rotor vertical offset h/R from the vehicle center of gravity. In general, the control power and damping due to vertical offset vary inversely as the first power of the size, whereas those due to equivalent hinge offset vary inversely as the square of the size. The net size variation then depends on the relative magnitudes of the vertical and hinge offset contributions to the control power and damping.

Referring to the equation for control power, the contributions are equal if

$$W\frac{h}{R} = \frac{W_R}{2g}\,\bar{R}\,\Omega^2\,\frac{e}{R}\;.$$

Inasmuch as

$$\frac{gW}{W_R\bar{R}\,\Omega^2} = \beta_o\text{, the blade coning angle,}$$

then the contributions are equal if

$$\frac{e}{R} = 2\,\beta_o\,\frac{h}{R}\;.$$

For a helicopter in the 4000-pound class, typical values are $h/R = 0.25$ and $\beta_o = 0.038$ radians. Then the contributions are equal if $e/R = 0.019$. For $e/R = 0.10$, the K_8, or hinge offset, terms are predominant (by a factor of $.1/.019 = 5.2$) in the size effect variations at this size. The hinge offset terms reduce relative to the vertical offset terms as the size increases, inasmuch as the coning angle β_o increases with size; from the above equation for β_o, it is seen that

$$\beta_o \sim L$$

if the rotor weight fraction and tip speed are invariant with size. Thus it may be seen that for $e/R = 0.10$, the contributions will be equal at a size such that β_o is 5.2 times as great; i.e., when the linear dimensions are approximately 5 times as great and the weight is about 125 times as great (gross weight = 500,000 pounds) as that of the 4000-pound vehicle.

EFFECT OF SIZE ON CONTROL REQUIREMENTS

EFFECT OF DISTURBANCES, JET VTOL

Wind and Gusts

Winds or gusts produce moments of the form

$$\Delta M = C_m \, qS\bar{c}$$

$$\Delta M \sim \rho V_g^2 L^2 L \sim L^3, \text{ since } \rho = \text{constant}, \ V_g = \text{constant}.$$

The resulting angular acceleration is:

$$\ddot{\theta} = \frac{\Delta M}{I} \sim \frac{L^3}{L^5} \sim \frac{1}{L^2} \, ,$$

indicating that the disturbing effects of winds or gusts decrease rapidly with increasing size. The disturbing effects of winds or gusts are most critical in roll and yaw for lateral gusts or lateral translation, and in pitch for gusts from the rear or for backward translation. These disturbances are appreciable contributors to control power and damping requirements for small vehicles, but relatively minor for large vehicles.

Interaction between the winds or gusts and the lifting jet inlets and exhausts creates pressure patterns on the upper and lower sides of the vehicle which produce moments tending to lift the upstream side of the vehicle for center-mounted jets. Assuming the significant pressure-pattern area does not extend beyond the vehicle planform, the pitch or roll moments produced are of the form

$$\Delta M \sim A_j D_j \quad \text{or} \quad \Delta M \sim A_j L \, ,$$

depending on arrangement of jet inlets and exhausts (i.e., whether inlets and exhausts are located in proportion to the jet diameter or vehicle characteristic length, such as with tip-mounted jets).

Where A_j is equivalent jet nozzle area,

D_j is equivalent jet nozzle diameter.

The precise point of application of force resulting from jet-induced pressures acting on vehicle requires more complete configuration analysis as contained in Reference 13.

The jet area is proportional to the weight of the vehicle, inasmuch as the thrust (which is proportional to weight) is:

$$T = \rho_j A_j V_j^{\,2} ,$$

where ρ_j is density of jet exhaust,

V_j is velocity of jet exhaust,

and ρ_j and V_j are relatively invariant.

Therefore, $T \sim W \sim A_j$

and $D_j \sim A_j^{\,1/2} \sim T^{1/2} \sim W^{1/2}$.

Therefore, $\Delta M \sim A_j D_j \sim W\,W^{1/2} \sim L^3 L^{3/2} \sim L^{9/2}$ for $M \sim A_j D_j$

$$\Delta M \sim A_j L \sim W\,W^{1/3} \sim L^3 L \sim L^4 \text{ for } M \sim A_j L \,.$$

The pitch or roll accelerations produced by this jet interference (for center-mounted jets)are of the form

$$\ddot{\theta} = \frac{\Delta M}{I} \sim \frac{L^{9/2}}{L^5} \sim \frac{1}{L^{1/2}} \text{ for } \Delta M \sim A_j D_j,$$

$$\ddot{\theta} = \frac{\Delta M}{I} \sim \frac{L^4}{L^5} \sim \frac{1}{L} \qquad \text{for } \Delta M \sim A_j L.$$

It may be seen that accelerations due to jet interference reduce slowly with increasing size.

In summary, then, the control power/inertia, M/I required to balance gust-induced disturbances, decreases with increasing vehicle size. With jet inlets and exhausts located in proportion to the length, the variation is of the form

$$\ddot{\theta} = \frac{\Delta M}{I} = \frac{K_9}{L^2} + \frac{K_{10}}{L}$$

where K_9 is a constant associated with gust-induced aerodynamic moments acting on the vehicle in the absence of jet interference, and K_{10} is a constant associated with the jet interference. Inasmuch as the available control power has been shown to vary inherently as 1/L, it is obvious that the control power required to offset gusts decreases more rapidly than the inherently available control power as size increases.

With near center-mounted engines having inlets and exits located proportional to jet diameter, the variation is of the form

$$\ddot{\theta} = \frac{\Delta M}{I} \sim \frac{K_9}{L^2} + \frac{K_{11}}{L^{1/2}}$$

where K_9 is defined as above and K_{11} is associated with the moments due to jet interference of engines having inlets and exits located proportional to jet diameter. Inasmuch as the lifting pressures at the extremities due to jet interference near the center must be small, it can be concluded that K_{11} is small with respect to K_{10}, or at the most no larger than K_9. It can therefore be concluded that in this case also the control power required to offset gusts decreases more rapidly than the inherently available control power as size increases.

Engine Failure

Assuming similar engine placement and the same number of engines as size increases, the moment due to engine failure is:

$$\Delta M \sim Tx_{cg} \sim WL \sim L^4 \qquad \text{where } x_{cg} \sim L$$

$$\Delta M \sim Tx_{cg} \sim L^3\, L^{3/2} \sim L^{9/2} \text{ where } x_{cg} \sim D_j \sim L^{3/2}$$

and the acceleration is:

$$\ddot{\theta} = \frac{\Delta M}{I} \sim \frac{L^4}{L^5} \sim \frac{1}{L} \quad \text{for } x_{cg} \sim L$$

$$\ddot{\theta} = \frac{\Delta M}{I} \sim \frac{L^{9/2}}{L^5} \sim \frac{1}{L^{1/2}} \quad x_{cg} \sim D_j \sim L^{3/2},$$

depending on whether the engines are located with respect to the center of gravity as a function of vehicle geometry or alternately as limited by engine diameter.

Ground Effect

The jet VTOL experiences a variation of vertical force with height in close proximity to the ground. As the height above the ground decreases, the vertical lift has been observed to increase for vehicles having jets located near the extremities and to decrease for jets arranged near the center. The decreasing force is explained by the reduction of pressure on the vehicle lower surface caused by the jet exhaust and entrained air having to increase velocity when the cross-sectional area of the flow becomes confined by reduction of height above the ground indicated in Figure 14. The increasing lift is caused by a portion of the radial ground flow from the jets being deflected upward as the jet streams from opposing sides meet near the center of vehicle as shown in Figure 15.

The following are accepted in considering this phenomenon:

V_j is independent of size and is constant even when spreading out along the ground (as flow spreads radially the depth of flow is decreased) except as modified by air entrainment and friction.

$M_j \sim W \sim V_j A_j \sim V_j L^2$.

Experiments indicate that the pressure on the lower surface is the same for vehicles having peripheral jets and the same geometry (particularly height/length) and jet velocity. The variation of lift force per unit of height/mass is derived through consideration of jet momentum and radial spreading of the opposing jets after striking the ground, Figure 15. The jet streams continue to expand radially in the vertical plane following the confluence midway between the jets.

$$F_z \sim m_j v_j \ \left[L/2\pi(b/2 + h)\right] \quad \text{and} \quad m_j v_j \sim W$$

$$dF_z/mdh \sim m_j v_j \ L/\pi \quad (b + 2h) \ W \sim 1/(1 + h/L).$$

The lift force per unit height/mass is constant for equal height/length values. The lift force per unit height/mass is increasing as height decreases, thereby stabilizing the vertical motion near the ground.

Tests show that entrainment of air by the lift jets is a primary effect for vehicles with center-mounted propulsion systems. The radial flow of the jet exhaust along the ground draws air under the vehicle lower surfaces as shown in Figure 14. The volume entrained is proportional to planform area and velocity:

Volume per unit time or $V_j \ S \sim V_j L^2$.

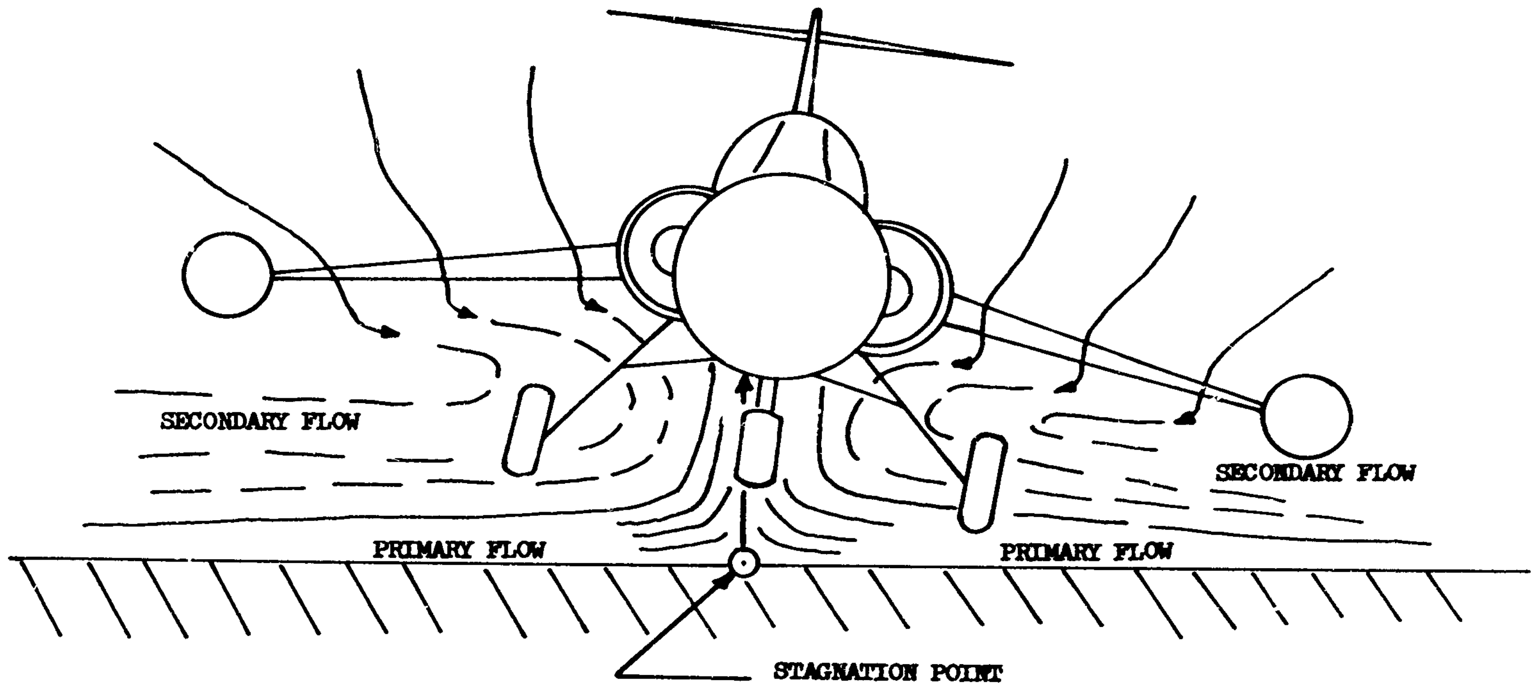


Figure 14 - Ground Effect, Center Mounted Jet

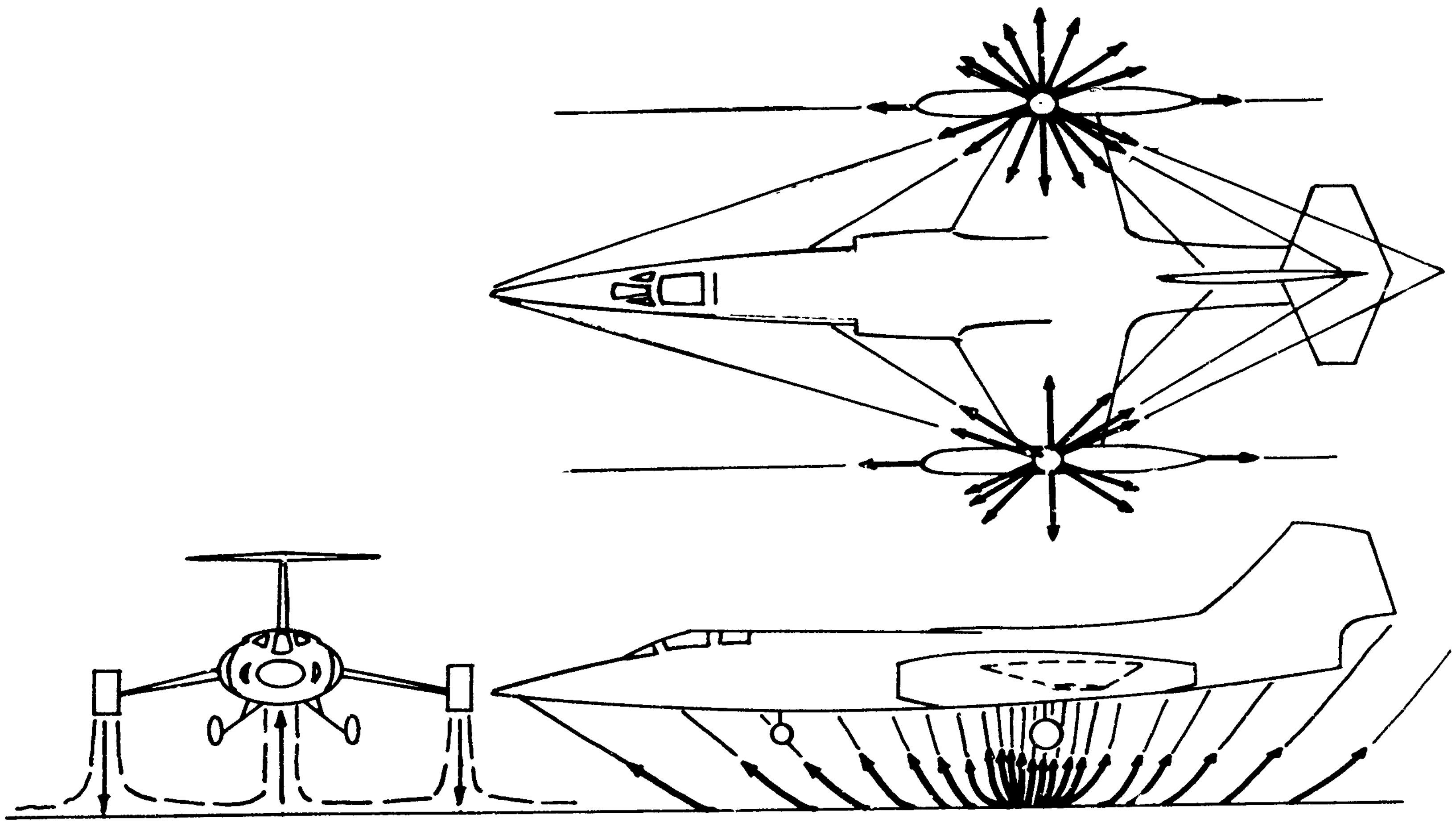


Figure 15 - Ground Effects, Tip Mounted Jets

Since the entrained air is drawn from around the periphery of the plan-form the flow area, A, and the mean entry velocity, V_e, may be expressed

$$A \sim ph \sim L^2$$

$$V_e = (\text{Volume flow})/A \sim V_j S/ph \sim V_j L^2/L^2 = \text{constant},$$

independent of vehicle size for constant geometric height (h/L).

The change of <u>lift force per unit of height/mass</u> is:

$$dF/mdh \sim (-S/m) \quad dV_e^{\,2}/dh \sim (-gS/W)\ V_j^{\,2} S^2/p^2 h^3$$

and $W \sim L^3$

$$dF/mdh \sim (L^2/L^3)\ (L^4/L^2L^3) \sim 1/L^2 .$$

The <u>lift force per unit of height/mass</u> for the center-mounted jets decreases with the square of the size. It should be noted that since lift is decreasing as height is decreased, the effect is destabilizing the vertical motion.

The jet VTOL vehicle also experiences an unstable moment variation with attitude change when in proximity to the ground. This moment is associated with the same phenomena as affect the lift variation with height, but is destabilizing whether caused by air entrainment in the radial ground flow from center-mounted jets or by impingement near center of the jet flows from tip-mounted jets.

Consider a vehicle with center-mounted jets. If the vehicle rolls through a small angle ϕ, the effective height is reduced on the low side and increased on the high side, causing a difference in the entrainment flow between the two sides.

$$\Delta V_e^{\,2} \sim \phi\, V_e^{\,2}\, \frac{h}{L} \sim \phi .$$

The unstable moment is:

$$\frac{\Delta M}{\phi} \sim \Delta V_e^{\,2}\, Sb \sim \Delta V_e^{\,2} L^3 \sim L^3 ,$$

and the acceleration varies as

$$\ddot{\theta}/\phi \sim \frac{\Delta M}{I\phi} \sim \frac{L^3}{L^5} \sim \frac{1}{L^2} .$$

Thus the unstable tendency due to entrainment decreases rapidly with increasing size.

With tip-mounted jets, a small roll angle results in an increase in inward flow momentum from the jet pointing inboard, and a corresponding decrease of inward flow momentum from the jet pointing outboard. The equal-momentum point at which the impinging jets turn upward is displaced toward the high wing by an amount

$$\Delta y \approx h\phi + KD_j\phi .$$

The proportion of the total momentum striking the wing is approximately

$$F = m_j V_j \; c/2\pi \; (h + b/2).$$

The moment per unit roll angle is

$$\frac{M}{\phi} = \frac{F\,\Delta y}{\phi} \approx \frac{m_j V_j \; c(h + KD_j)}{2\pi \; (h + b/2)} \sim \frac{WL\;(L + KL^{1.5})}{L}$$

$$\frac{M}{\phi} \sim L^4 + KL^{4.5}$$

$$\frac{\ddot{\phi}}{\phi} = \frac{M}{\phi I} \sim \frac{1}{L} + \frac{K}{L^{0.5}} .$$

The angular accelerations due to impingement of jet flows from tip-mounted engines decrease with increasing size.

EFFECT OF DISTURBANCES, HELICOPTERS

Yaw

The yaw angular acceleration produced by a sudden wind or gust on a hovering helicopter is:

$$\ddot{\Psi} = \Delta M/I = l_T(dT/dV_g)\; V_g/I \sim LW/(K_6 + W^{1/2}/L)\; WL^2$$

$$\ddot{\Psi} \sim 1/L\; (K_6 + L^{1/2}) \quad \text{for } W \sim L^3$$

$$\ddot{\Psi} \sim 1/L \qquad\qquad \text{for } W \sim L^2$$

where V_g is constant and dT/dV_g is similar to dT/dV_V, derived previously.

The tail rotor collective pitch control θ_t required to counter this disturbance is:

$$\theta_t = \Delta M/M_c \sim [1/L\ (K_6 + L^{1/2})\ V_g\ ]/[1/L(K_6 + L^{1/2})]$$

$$\theta_t \sim V_g = \text{constant for } W \sim L^2 \text{ or } W \sim L^3.$$

Pitch and Roll

The pitch and roll angular accelerations caused by a horizontal wind or gust are derived as follows. The moment on the main rotor is based on a constant chord, ideally twisted blade with uniform downwash. Results are similar for blades having moderately different geometry:

$$\Delta M = \int_0^R \int_0^{2\pi} (\rho/2)\ (\Omega r + V_g \sin\Psi)^2\ abc(r \sin\Psi)$$

$$[(\theta_t R/r) + \theta_c \sin\Psi - v/(\Omega r + V_g \sin\Psi)]\quad dr d\Psi/2\pi$$

$$\Delta M = (\rho/4)\ (\Omega R)^2\ abcR^2\ \left[\theta_t - \phi_t\ + \theta_c\ (3\mu_g^2\ + 2)/8\mu_g\right]\mu_g.$$

Where $T = (\rho/4)\ (\Omega R)^2\ abcR\ (\theta_t - \phi_t) = W$ from Reference 12, page 58,

$\theta_c = 0$, and μ_g = constant, then the initial rotor precession rate is:

$$\dot\theta\ = \Delta M/J_R\Omega \sim WR\mu_g/WR^2\Omega = \text{constant}.$$

The initial precession rate is invariant with size or rotor type (rigid or articulated).

The cylic pitch required to counter the precessional moment caused by a horizontal wind or gust (setting $\Delta M = 0$) is:

$$\theta_c = -8\alpha_b\ \mu_g/(3\mu_g^2 + 2).$$

Since α_b is independent of size or rotor type (see page 17) and M_g is likewise the same for a given gust, the cyclic pitch required to counter the gust is identical.

Since $M_A \gg K_\beta$, the rotor angular tilt is nearly the same for both articulated and rigid rotor if the shaft and swash plate are fixed because the tilt of the rotor changes the cylic pitch of both rotors in the same manner. However, the swash plate and shaft of the unstabilized rotor are not fixed and follow the motions of the rotor in continuing to precess. The gyro stabilizer fixes the swash plate, providing corrective cyclic pitch. It is necessary for the pilot of the vehicle with unstabilized

rotor to apply all of the gust correction. The attendant lags in pilot input will increase the disturbed motion of the unstabilized rotor with respect to the motion of the stabilized rotor.

Although the initial rotor precession rate in response to a disturbance is invariant with size, the fuselage angular acceleration decreases with increasing size. This may be seen by noting that at any given rotor tilt,

$$\ddot{\theta} = \frac{M}{I} \sim \frac{1}{L} + \frac{K_8}{L^2} \quad .$$

PILOT-VEHICLE COMPATIBILITY

Pilot Characteristics

Inasmuch as the pilot characteristics are inherently involved in flying qualities criteria, certain basic assumptions as to the pilot characteristics should be made in considering size effect (these assumptions are not new and are frequently considered by other investigators, as reported in Reference 19):

1. The pilot is experienced in the type.

2. The pilot is an adaptive servo.

3. For motions larger than the minimum perceptible the pilot is a semilinear servo with appropriate phasing for the vehicle.

4. A requirement that the pilot augment the damping of the vehicle (by providing lead phasing, or anticipatory control) increases the learning time and the susceptibility to error.

   a. The error susceptibility increases as the time available for correction decreases: that is, as the pilot-vehicle motion frequency increases.

   b. The pilot is unable to provide damping for vehicle motion frequencies (in radians/second) in the order of $\omega \sim 1/t_p$, the inverse of the pilot perception-reaction time.

5. For motion magnitude of the order of the pilot's minimum perception the pilot's response is nonlinear.

6. For small motions the pilot adapts to find a control input which gives a vehicle motion response that is of the order of magnitude of the pilot's minimum perception level.

to which two corollaries may be added:

7. The type of control deflection giving minimal response is generally an impulsive (force-time or deflection-time integral) type of control.

8. If the minimum control pulse provides excessive response, the pilot will be unable to avoid a continued oscillation.

Size Effect on Pilot-Vehicle Dynamic Stability

The above-stated pilot characteristics, in combination with the previous discussions of the control power/inertia and disturbance susceptibility variations with size, would indicate that very small VTOL vehicles might be difficult to fly. The smaller vehicles inherently have high control power relative to their inertia, and require this control power to offset external disturbances. This characteristic implies that the minimum control input available to the pilot may be excessive, leading to his overcorrecting observed angular rates and being unable to reduce them to less than his perception level. This characteristic will be aggravated by friction in the control system, which tends both to increase the overcorrection and to introduce lag in the control application.

The time to achieve a perceptible angular rate $\dot{\theta}_p$ due to a disturbance or control input is:

$$t = \frac{\dot{\theta}_p}{\ddot{\theta}} .$$

For the jet VTOL aircraft, $\ddot{\theta} \sim 1/L$. Therefore $t \sim \dot{\theta}_p L$. The time will increase even more rapidly with size for other vehicles (as seen by the equations for acceleration in Table 1). This indicates that the time available to the pilot to perceive and react to an angular rate increment is less with small vehicle size. Thus the possibility of pilot-coupled oscillations tends to be greater in smaller vehicles.

Such a tendency toward difficulty in flying has been observed in some one-man helicopters. Another instance was observed during flight testing of a 2-place rigid rotor helicopter, in which an experimental control hookup resulted in a stable but lightly damped mode of body pitching opposite rotor pitch at about 0.7 cps, or $\omega = 4.5$ rad/sec. This corresponds to $t = 1/\omega = 0.22$ sec., indicating that the characteristic time might be less than the pilot's perception-reaction time. The pilot found that any attempt to control or damp this mode resulted in unstable pilot-coupled vehicle oscillations that could only be stopped by freezing the controls and thereafter not responding to this mode. This experiment was repeated several times with the same result. The structural coupling that caused the low damping of this mode was then removed.

Limitations in Providing Damping

The limitations of the pilot function in providing damping may be examined quantitatively in terms of a linear damper servo mechanism. Flight experience with these systems has shown that the allowable damper gain is limited by the occurrence of sustained oscillations at a frequency corresponding to that at which the phase lag of the damper system just exceeded 90 degrees. The criterion for stability of the system is that the gain C/I at the frequency for 90-degree system lag be less than that frequency in radians per second. This follows from the fact that at $90 + \epsilon$ degrees lag, the "damper" acts as a spring with negative damping. The equivalent spring constant $K_e\theta$ is determined from $K_e = (C\dot{\theta})_{\phi=90^\circ} = (C\omega\theta)_{\phi=90^\circ}$. Therefore $K_e/I = (C\omega/I)_{\phi=90^\circ}$. But $K_e/I = \omega^2$, the square of the oscillation frequency producible by the damper gain. Therefore if $(C\omega/I)_{\phi=90^\circ} > \omega^2_{\phi=90^\circ}$, giving $(C/I)_{\phi=90^\circ} > \omega_{\phi=90^\circ}$, then the damper system gain is high enough to produce an unstable oscillation at the frequency for 90-degree system lag. The criterion for stability is then

$$(C/I)_{\phi=90^\circ} < \omega_{\phi=90^\circ} .$$

This criterion assumes that the vehicle frequency without servo is negligible relative to $\omega_{\phi=90^\circ}$. The allowable gain decreases rapidly as the vehicle basic frequency approaches the servo system 90-degree lag frequency, becoming zero when the two frequencies are equal.

In terms of the pilot, it may be assumed that, for normal control involving only small control motions, $\omega_{p_{\phi=90^\circ}} \approx 1/\tau_p \approx 4$ rad/sec. This relation implies that the pilot's contribution to damping a vehicle cannot exceed $(\Delta C/I) \approx 4$ radians/second and that this contribution must be decreased as the vehicle basic frequency approaches 4 radians/second, or if there are additional sources of phase lag in the control system. In the vehicle frequency range from 4 to about 9 radians/second, the pilot inputs can be expected to be dynamically destabilizing if the pilot assumes he must control these motions. Experience has led to recommendations such as shown in Reference 5, Figure 8, requiring high damping ratios for any vehicle modes in this frequency range.

The foregoing discussion also indicates that care must be used in the design of servo systems for augmenting VTOL vehicle damping to avoid damaging lags that would unduly limit the allowable gain. Typical servo damper systems for fighter aircraft have 90° lag frequencies of 20 radians/second and higher, indicating that gains as high as C/I = 20 are easily available if within the limits of control power allocated to damping.

In view of the damper gains of order $C/I = 20$ available in conventional aircraft, it appears that damper gains of order $C/I = 2$ to 2.5, corresponding to time constants of 0.5 to 0.4 second as proposed by Curry and Mathews (Reference 5), are entirely feasible. This requires a system with a 90° lag frequency greater than 2.5 rad/sec, or 0.4 cps. For the helicopter this minimum system frequency would probably require a rotor rotational frequency definitely greater than 2.5 rad/sec, say 5 rad/sec. At 700 fps tip speed, this would imply a rotor no larger than $R = 700/5 = 140$ ft., or 280 ft. diameter. Therefore it does not appear to be a limitation for helicopters in the near future.

With respect to damper gains for jet VTOL aircraft, those using thrust modulation will be limited in allowable gain by the time constant of the lift engines. This limitation applies to height and/or attitude control for all jet or fan lift VTOL craft using engine or fan speed to control lift and/or attitude. A typical jet engine in the 2000-pound thrust class may have a first-order time constant of about 0.25 second. The inverse of the time constant is the circular frequency ω_e at which the lag is 45 degrees, in this case $\omega_e = 4$ rad/sec. In view of other lags in the system, it may be assumed that the frequency for 90-degree phase lag will be not greater than $\omega_{90°} = 2\omega_e$, in this case about 8 rad/sec. This result would indicate a maximum vertical damping gain C_V/m somewhat less than 8 for engines in this size class. For an engine of twice the diameter (8000-pound thrust), the time constant is twice as great, indicating a maximum vertical damping gain C_V/m less than 4.

If the same thrust modulation is also used for attitude control, the maximum angular damping gain C/I is related to the height damping gain C_V/m by the square of the ratio of the engine distance ℓ_e from the applicable axis to the vehicle radius of gyration k about that axis. That is, $C/I = (C_V/m) \sum \left(\frac{\ell_e}{k}\right)^2$. This relation would indicate that engines placed further out than the vehicle radius of gyration could provide a higher angular damping than linear damping, and that engines inside the vehicle radius of gyration would provide a low damping ratio. For example, lift engines in wing tip pods could be expected to provide a reasonable value of C/I in roll, but poor C/I in pitch, since the engines are further out laterally than the roll radius of gyration, but the fore-and-aft spread of the engines is small relative to the pitch radius of gyration. It has been shown in the JET VTOL section of EFFECT OF SIZE ON HANDLING CAPABILITY that damping/inertia of jet VTOL aircraft is decreased with increased size.

Accuracy of Control

The question of accuracy of maneuvering is related to vehicle size in terms of both dynamic stability of the pilot-vehicle combination and of

vehicle susceptibility to external disturbances. Accuracy is particularly involved in hovering/flying near obstacles, aiming or firing guns, and in IFR flight.

Aiming or firing and IFR flight are examples of maneuvers requiring angular accuracy. This accuracy is reduced by response to external disturbances and by excessive response to controls, and is increased by increased damping. On this basis it would appear that very small vehicles, having excessive control power (poor pilot-vehicle compatibility) and gust sensitivity would be relatively less accurate than larger vehicles having better compatibility and less gust sensitivity. In vehicles large enough for satisfactory pilot-vehicle compatibility, the effects of reducing gust sensitivity tend to increase accuracy with increasing size. On the other hand the reducing inherent damping with size tends to reduce accuracy.

In the absence of external disturbances, the maximum angular error occurs if the angular error and error rate reach their respective perception thresholds at the same time. The maximum angular error is:

$$\theta_{\epsilon_{max.}} = \theta_{\epsilon_p} + K_{13}\,\dot{\theta}_{\epsilon_p}\,\tau_p$$

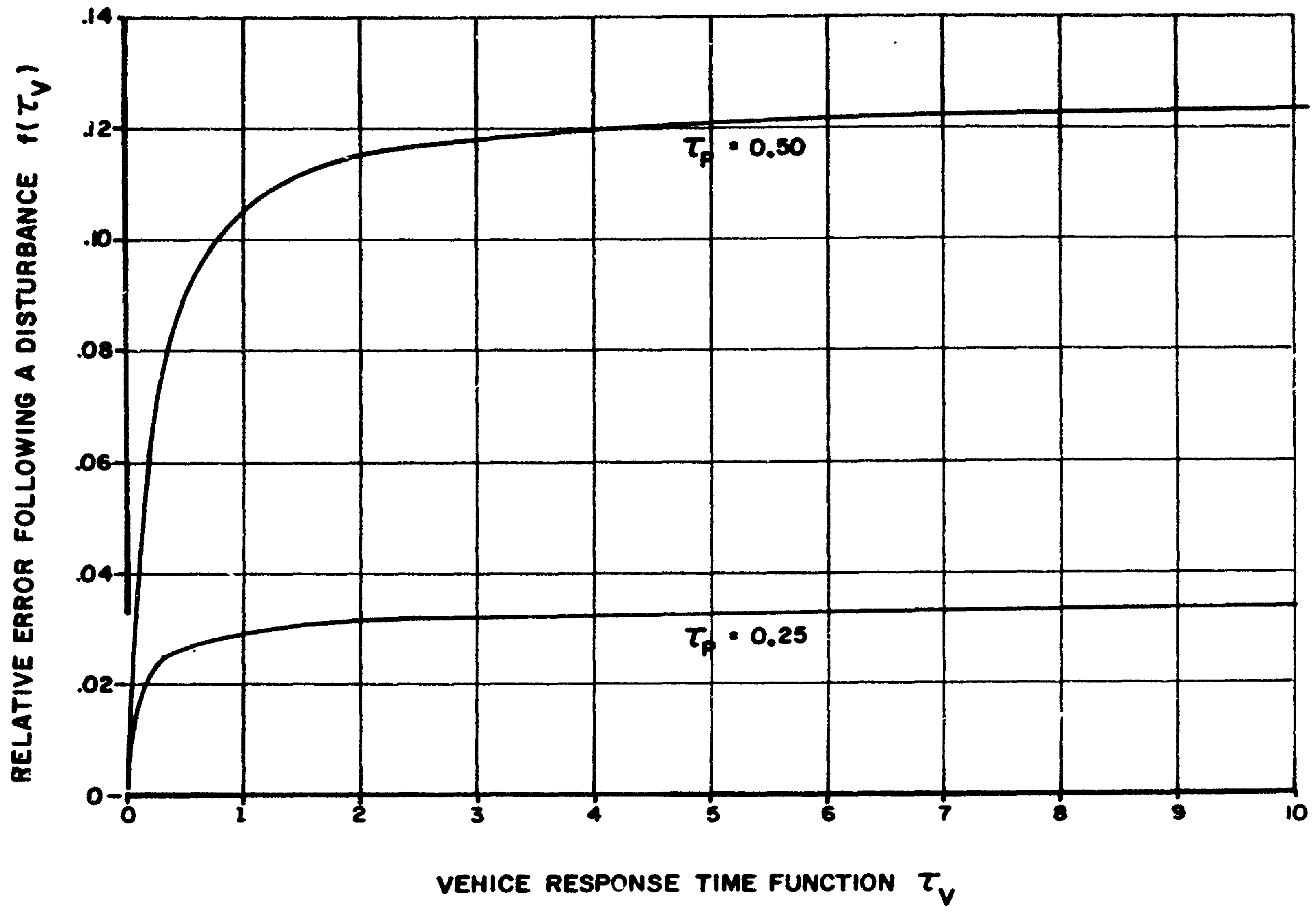
where K_{13} will have a value between 1 and about 2, depending on the magnitude of the corrective control impulse which is applied at time τ_p after the threshold error occurs. The accuracy in the absence of disturbances then depends primarily on the perception accuracy and is independent of size, unless the size can be used to increase the perception accuracy.

In the presence of external disturbances giving displacements appreciably larger than the threshold, the angular displacement at the time τ_p at which the pilot takes corrective action is:

$$\theta_{\tau_p} = (\Delta M/I)\left[\tau_p\,\tau_v - \tau_v^2\,(1-e^{-\tau_p/\tau_v})\right] = (\Delta M/I)\;f(\tau_v)$$

where τ_v is the vehicle time constant, and $\Delta M/I$ is the step disturbance magnitude relative to the vehicle inertia; i.e., the initial angular acceleration. The total excursion is expected to be not much greater than θ_{τ_p}, inasmuch as the corrective impulse is assumed to be applied at time τ_p and to be properly sized to correct and return the vehicle. The value θ_{τ_p} is therefore reasonably proportional to the maximum excursion.

The factor in brackets, $f(\tau_v)$, is plotted on Figure 16 as a function of vehicle time constant τ_v for two values of the pilot time constant τ_p. These values are τ_p = 0.25 sec., representative of normal small-deflection


RELATIVE ERROR FOLLOWING A DISTURBANCE $f(\tau_V)$
.14
.12
.10
.08
.06
.04
.02
0
τ_P = 0.50
τ_P = 0.25
0
1
2
3
4
5
6
7
8
9
10
VEHICE RESPONSE TIME FUNCTION τ_V

control, and τ_p = 0.5 sec., representative of large control deflections or of poor motion cues and visual cues by which to control. It is apparent from these plots that little reduction of the excursion magnitude is obtained from the vehicle damping if the vehicle time constant τ_v is greater than the pilot time constant τ_p.

On the other hand, large reductions in the excursion magnitude are obtainable if τ_v is made less than τ_p; that is, if the vehicle damping is made larger than that which the pilot can supply. It is of interest that conventional aircraft have time constants less than that of the pilot and generally require no auxiliary damping, whereas VTOL vehicles (except the rigid rotor with stabilizing gyro) have time constants greater than that of the pilot and benefit from additional damping.

The effects of size on the angular accuracy in the presence of gust disturbances may be evaluated from the variations of $\Delta M/I$ and of $f(\tau_v)$ with size. The initial acceleration $\Delta M/I$ has been shown to decrease with increasing size as a function between first and second power. The vehicle time constant has been shown to increase with the first power of size. A reasonable curve fit indicates that $f(\tau_v) \sim K_{\tau_v}{}^{0.1}$ from τ_v = .25 to τ_v = 1.0. Therefore,

$$\theta_{max.} \sim \theta_{\tau_p} \sim \frac{\Delta M}{I} f(\tau_v)$$

$$\frac{\Delta M}{I} \sim \frac{1}{K_{14}L + K_{15}L^2} \text{, where } K_{14}, K_{15} \text{ depend on configuration,}$$

$$f(\tau_v) \sim \tau_v{}^{.1} \sim L^{.1} ,$$

then

$$\theta_{max.} \sim \frac{L^{.1}}{K_{14}L + K_{15}L^2} \sim \frac{1}{K_{14}L^{.9} + K_{15}L^{1.9}} .$$

Therefore, it is concluded that the maximum angular error due to a disturbance decreases with size, and is not significantly reduced by augmenting the vehicle damping unless the augmented damping is greater than that which the pilot can supply. Exceptions to this statement follow:

1. In the case of very large disturbances such as those caused by failure of an offset lift engine, there is an additional pilot lag associated with the pilot's adaptive mechanism: he must adapt suddenly from use of small control inputs to much larger inputs, and this creates an appreciable additional lag which may be called the adaptive lag. The total pilot lag in applying sufficient control in such cases may vary from 0.5 sec. to 1.0 sec. In this case augmented damping will be of great benefit in reducing the vehicle response.

2. In normal operation, vehicle damping of the same order as or greater than that otherwise supplied by the pilot relieves the pilot work load, permitting more attention to mission and reducing susceptibility to error due to fatigue.

IFR Control

The outstanding characteristic of flight by reference to instruments is the lack of the instantaneous attitude and position information which is available by direct or peripheral vision under visual flight conditions (as noted by the authors and other observers). The use of his peripheral vision under VFR conditions allows the pilot to maintain quick reactions for flight control while conducting other tasks. The VFR reaction time is necessarily slowed under IFR conditions by the fact that

1. A minimum of two instruments - artificial horizon and direction gyro - is usually required for attitude control, and a third, the turn/bank, is also scanned. Time is lost in shifting and focusing on each instrument in turn.

2. Some percentage of the time is unavailable for attitude and position control while scanning engine condition instruments, etc.

3. In the VTOL mode, three-axis linear position information and control assume equal importance with attitude information and control. If past practice were followed, at least two instruments would be added for this purpose, making it necessary to scan at least four essential instruments to control the aircraft. Assuming that 80 percent of the time is devoted to the four essential instruments, each instrument would get 20-percent attention. This fact indicates that the pilot's perception-reaction time may be increased nearly fivefold relative to VFR by the mode of information presentation.

From previous discussions, large increases in pilot reaction time indicate corresponding decreases in his ability to provide vehicle damping and increases in the vehicle attitude errors due to external disturbances. In the VTOL mode, the corresponding linear position and velocity errors would be unacceptable. This decrement in capability can be compensated for by vehicle damping, which in the VTOL mode may need to include linear damping in height and horizontal translation as well as angular damping in pitch and roll.

An interesting alternative suggested by other investigators (such as those given in Reference 10) is the possibility of providing all attitude and position information in one presentation. This may be a head-up presentation involving projection of a simulated ground with landing target, or an instrument presentation on one dial requiring no eye shifting. The pilot IFR reaction times may be shortened to the order of VFR

times, and accuracy could conceivably be increased. Thus it appears that completely blind takeoffs and landings would be practicable with the proper form of data presentation to the pilot. Emphasis should be given toward development to this end.

The effect of size in IFR operation is most apparent in the response to external disturbances. In conventional aircraft, pilots report that large transport aircraft are easier to fly IFR than light planes because of their slower response to disturbances. This slow response makes long pilot reaction times more acceptable, and is presumably one of the reasons why good data presentation for the pilot has not been adopted. More importantly, however, conventional aircraft have not required fast reactions for damping about any axis, or for control about any axis other than roll.

Hovering

The task of hovering normally involves small control motions wherein maximum control power is not involved unless the vehicle is highly susceptible to external disturbances or has attitude instability in ground effect. If maximum control power requirements are determined from vehicle flight tests in hover and low-speed maneuvers, care should be taken in attempting to apply these requirements to vehicles of other sizes in view of the rapid variation of vehicle susceptibility to trim changes, external disturbances, and attitude instability with vehicle size.

Control power requirements in the absence of two of these effects (gusts and ground effect instability) can be investigated by use of variable-stability aircraft which can be adjusted to cancel vehicle angular accelerations, due to any causes other than pilot inputs. If adequate airspeed sensors are available, trim changes due to speed can also be canceled.

More important to the experimental investigation of the effects of size on handling qualities criteria, however, is the fact that such a variable-stability VTOL research vehicle can be adjusted to represent the acceleration response to disturbances and the trim changes with speed of any size vehicle from very small to very large. Control power and damping criteria appropriate to these characteristics can then be determined. Some of these data are provided in Appendix IV.

It is recommended that such experimental investigations of the effects of size on handling qualities criteria be conducted before definitive criteria are adopted. The NASA Ames X-14A VTOL research vehicle and the NASA Langley variable-stability helicopter are adaptable to this research. With each change in simulated vehicle size, sufficient flight time should be allowed for the pilot to adapt to the "feel" of the vehicle before quantitative evaluation is undertaken.

Pilot Acceleration Effects

It has been shown that the vehicle angular accelerations due to control inputs decrease linearly with increasing vehicle size,

$$\ddot{\theta} \sim 1/L \; .$$

Since the pilot distance from the vehicle center of gravity is proportional to size (Appendix II), his linear acceleration due to an angular control input,

$$\ddot{Z}_p \sim \ddot{\theta} L = \text{constant},$$

is independent of size. This initial linear acceleration of the pilot will not be properly simulated in a fixed-size research vehicle simulation of size effects, nor will pilot linear accelerations due to external disturbances. The ratio between linear accelerations due to control inputs and those due to external angular disturbances will, however, be preserved.

Effect of size on the centrifugal acceleration applied to the pilot by vehicle rotation velocity is derived as follows. It has been shown that the angular velocity is:

Jet VTOL aircraft

$$\dot{\theta},\ \dot{\phi},\ \dot{\psi} = \text{constant}$$

Helicopters

$$\dot{\theta},\ \dot{\phi} = \text{constant}$$

$$\dot{\psi} \sim 1/L \; .$$

Then using the relation that pilot's distance to the vehicle center of gravity is proportional to characteristic length, his centrifugal acceleration due to angular rate is:

Jet VTOL aircraft

$$\ddot{x} \sim \dot{\theta}^2 L \sim L$$

$$\ddot{x} \sim \dot{\psi}^2 L \sim L$$

$$\ddot{z} \sim \dot{\phi}^2 L \sim L \; .$$

Helicopters

$$\ddot{x} \sim \dot{\theta}^2 L \sim L$$
$$\ddot{x} \sim \dot{\psi}^2 L \sim 1/L$$
$$\ddot{z} \sim \dot{\phi}^2 L \sim L.$$

Optical Effects

The large VTOL vehicle hovers with the pilot higher off the ground than does the small vehicle. The pilot's accuracy in perceiving position and velocity is diminished in proportion to his height, but remains in proportion to the vehicle size. Inasmuch as he will tend to maintain his clearance of any near obstacles in proportion to vehicle size, his relative accuracy is independent of size. A noticeable effect of larger size, however, is that greater time is used in acquiring a perceptible velocity or position error following a given attitude change. This lengthening of the time scale with increasing size eases the pilot task in hovering, just as has been observed for the size effect in IFR flight.

It should be noted that optical effects associated with size occur only in relatively close proximity to ground or obstacles. At distances beyond about twice the vehicle characteristic dimension, judgement of distance and speed is based on binocular vision, apparent size of familiar objects, perspective effects, etc.

MISSION-ORIENTED CONTROL REQUIREMENTS

The most obvious limitations of increased size are associated with flight near obstacles. The large vehicle cannot land in all the same clearings available to the smaller vehicle, nor can it fly in all the same channels. For a given twisting channel that both can fly through, the larger vehicle must fly slower because its turns are necessarily sharper than those of the smaller vehicle. The larger vehicle must also fly slower in contact flight with severely restricted visibility, inasmuch as the vehicle extends to a larger percentage of the visible field.

The jet VTOL, because of its limited hover time, has no mission at low speeds other than to take off and accelerate to flight speed, then to convert to hover and land at the end of its flight. Typical maneuvers associated with these tasks are discussed in References 8 and 14. The associated control power requirements are relatively low. Because of its higher wing loading, the large vehicle covers a greater speed range from the stall speed to hover,

$$\Delta q \sim \frac{W}{S} \sim L$$
$$\therefore \Delta V \sim \sqrt{L} \cdot$$

Since linear deceleration or acceleration is invariant with size

$$\Delta t \sim \Delta V \sim \sqrt{L} \, .$$

The deceleration time (and distance) increase with size. The trim changes are proportional to

$$\Delta M = C_m q S \bar{c} \sim L L^2 L \sim L^4$$

and

$$\frac{\Delta M}{I} \sim \frac{L^4}{L^5} \sim \frac{1}{L} \, .$$

The control power/inertia required to trim center of gravity changes to allow for expendable load items such as fuel and military items, and to give some flexibility in loading the aircraft (based on center of gravity limits as a constant percentage of characteristic length as is normal practice)is:

$$\frac{\Delta M}{I} \sim \frac{WL}{WL^2} \sim \frac{1}{L} \, .$$

These relations show that the control power/inertia required to balance trim changes decreases with increasing size and (in the case of speed changes) that the time available to compensate for these reduced trim changes is greater. These variations are in balance with the variation of capability with size.

Helicopters, because of their greater hovering efficiency, have a number of missions in the hover and low-speed range. These may vary from pole setting, winch rescue and sonar dipping to "pop-out" combat from behind cover.

The "pop-out" maneuver is likely to require maximum control power, inasmuch as the pilot wants to appear and disappear as rapidly as possible. The vertical pop-up involves lift control power, F_{CV}/m, which for a fixed increment of collective pitch decreases only slowly with size (page 35), but which is independent of size for a fixed increment of blade lift coefficient or fixed percentage increment of power. It is therefore expected that the vertical acceleration capability will not vary appreciably with size.

Horizontal accelerations for popping out laterally are produced by tilting the rotor laterally, the acceleration being $\ddot{y} = g \sin \phi_R$. The rate of rotor tilt per unit of feathering angle is:

$$\dot{\phi}_R = \frac{M_A}{J_R \Omega} \sim \frac{L^4}{L^5/L} = \text{constant},$$

from which it may be said that, to the first approximation, the lateral acceleration is also independent of size so long as the droop stops are not hit because of lag in fuselage roll response behind the rotor. The lag is due to the fact that the rotor, being hinged or flexible, tilts more rapidly than the fuselage.

It should be noted that there is a small lag in development rotor roll rate not shown by the usual gyro precessional equation. This lag is of order $\tau \approx 1/\Omega$ and can therefore be safely neglected in these discussions; this lag does, however, increase linearly with rotor size, since $\Omega \sim 1/L$.

Inasmuch as the initial lateral acceleration is nearly independent of size, and the lateral acceleration occurring after the rotor-fuselage tilt is developed is also independent of size, it may be concluded that the capability to perform a given lateral translation maneuver (in feet of lateral movement) is nearly independent of size. The "pop-out" maneuver, however, normally requires a motion of about one rotor diameter, so that the time required increases with size.

In general, then, linear acceleration capabilities of the helicopter are nearly invariant with size although the angular acceleration capability decreases with size. Inasmuch as mission capability depends primarily on linear capability, it appears that mission capability is nearly invariant with size except for those cases in which the size itself is the limiting factor.

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APPENDIX I

DAMPING AND CONTROL POWER DERIVATION

The damping/inertia value shown in Figures 1, 2, and 3 of the Introduction to this report were computed from the equations of Table 2 and moments of inertia for the indicated axis and weight given in Appendix II, Figure 23.

The control power/inertia values shown in Figures 4 through 13 of the Introduction were calculated from damping/inertia (above) and the angular displacement and time given in Table 2 corresponding to axis and weight indicated. The following equations were used:

For zero system time lag -

$$M_c/I = \theta\, C/I \left[t - (I/C)(1 - e^{-tC/I})\right]$$

For 0-2 second system time lag -

$$M_c/I = \theta\, C/I \left\{t - 0.2 - (I/C)\left[1 - e^{(0.2-t)\, C/I}\right]\right\}.$$

Where angular rate is specified in Table 2, the control power/inertia ratio was obtained from the expression:

$$M_c/I = \dot{\theta}\, C/I.$$

The damping/inertia determined from the criteria of Reference 5 was computed on the following basis:

$$C/I = 1/(\tau - \tau_L)$$

where

τ is the response time given in Reference 5,

and

τ_L is the system time lag.

The final angular rate used in computing the control power/inertia from Reference 5 was assumed to be the product of the limit control force for hover specified in Figure 4, Reference 5 and the maximum steady state angular velocity per unit control force specified in Figure 5, Reference 5. It is recognized that the control system lag generally increases with size and, consequently, the damping and control power must increase with size to maintain constant response time and constant angular velocity relation. Since system time lag varies with configuration as well as size, the constant values shown in Figures 1, 4, 7, 10 and 12 may be misleading. Curves are shown in Figure 4 and 10 for zero system time lag and Figures 7 and 12 for 0.2 second time lag.

APPENDIX II

VEHICLE CHARACTERISTICS

The characteristics of non-VTOL and VTOL flying vehicles, including helicopters, are given as a function of gross weight in the following figures:

Figure	
17	Span
18	Length
19	Distance from pilot's eye to vehicle center of gravity
20	Distance from pilot's eye to ground (vehicle on ground)
21	Distance from pilot's eye to vehicle forward extremity
22	Wing Loading and Disc Loading
23	Moments of Inertia

The symbols in the figures represent the following vehicles:

Non-VTOL	VTOL	
T-37C	B-2	XC-142A
F-104G	CH-1C	X-19A
F-4B	269A	XV-4A
Super DC-3	HU-1B	XV-5A
DC-6	OH-5	P-1127
DC-7	XH-51	BALZAC
DC-8	S-60	
720	S-61L	
727		

The trend lines drawn through the data for span and for length are in agreement with trends shown in Reference 9, Page 15, and Reference 15, Page 19. The lines drawn for moment of inertia data were taken from Reference 15, Page 19.

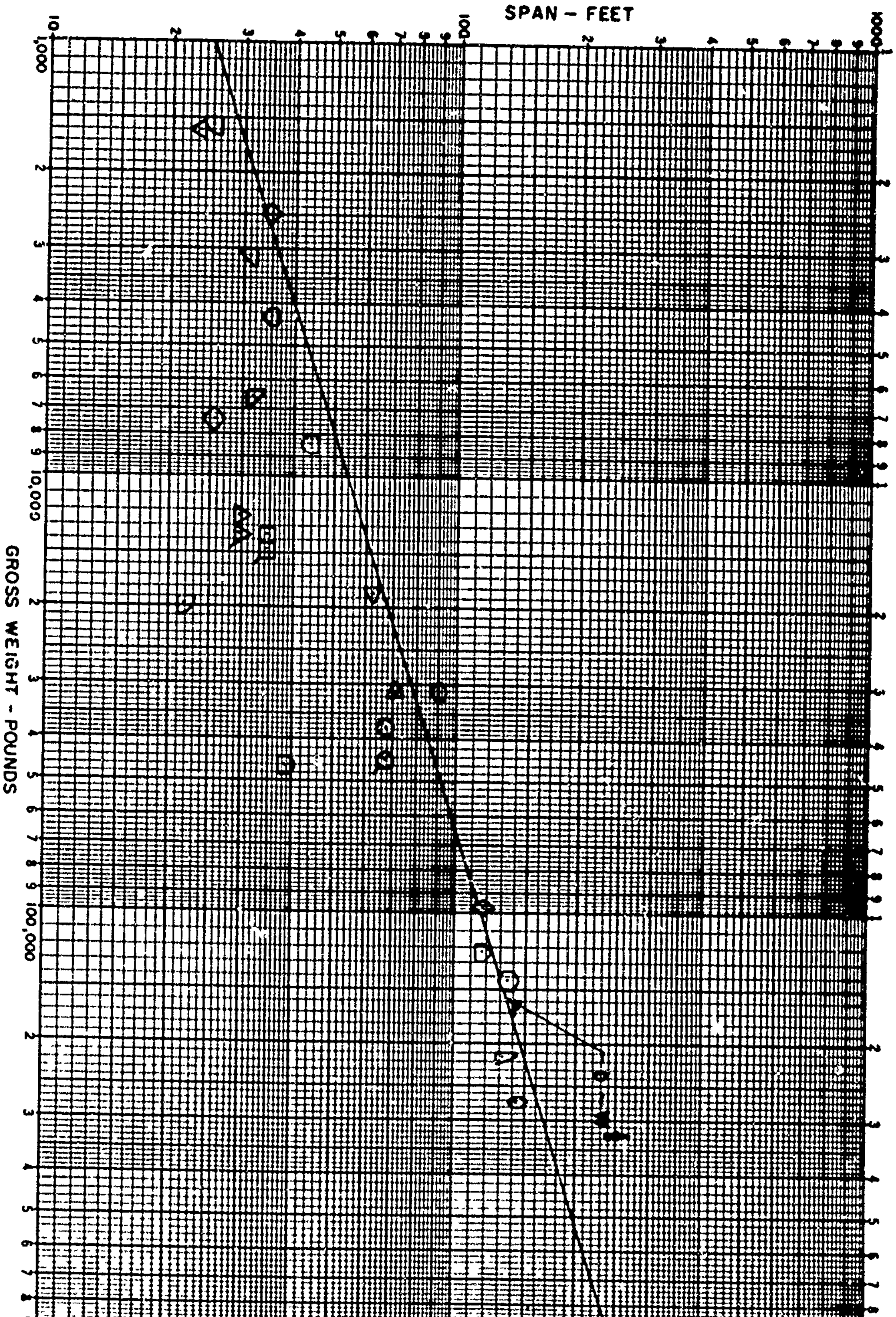

Figure 17 - Vehicle Span

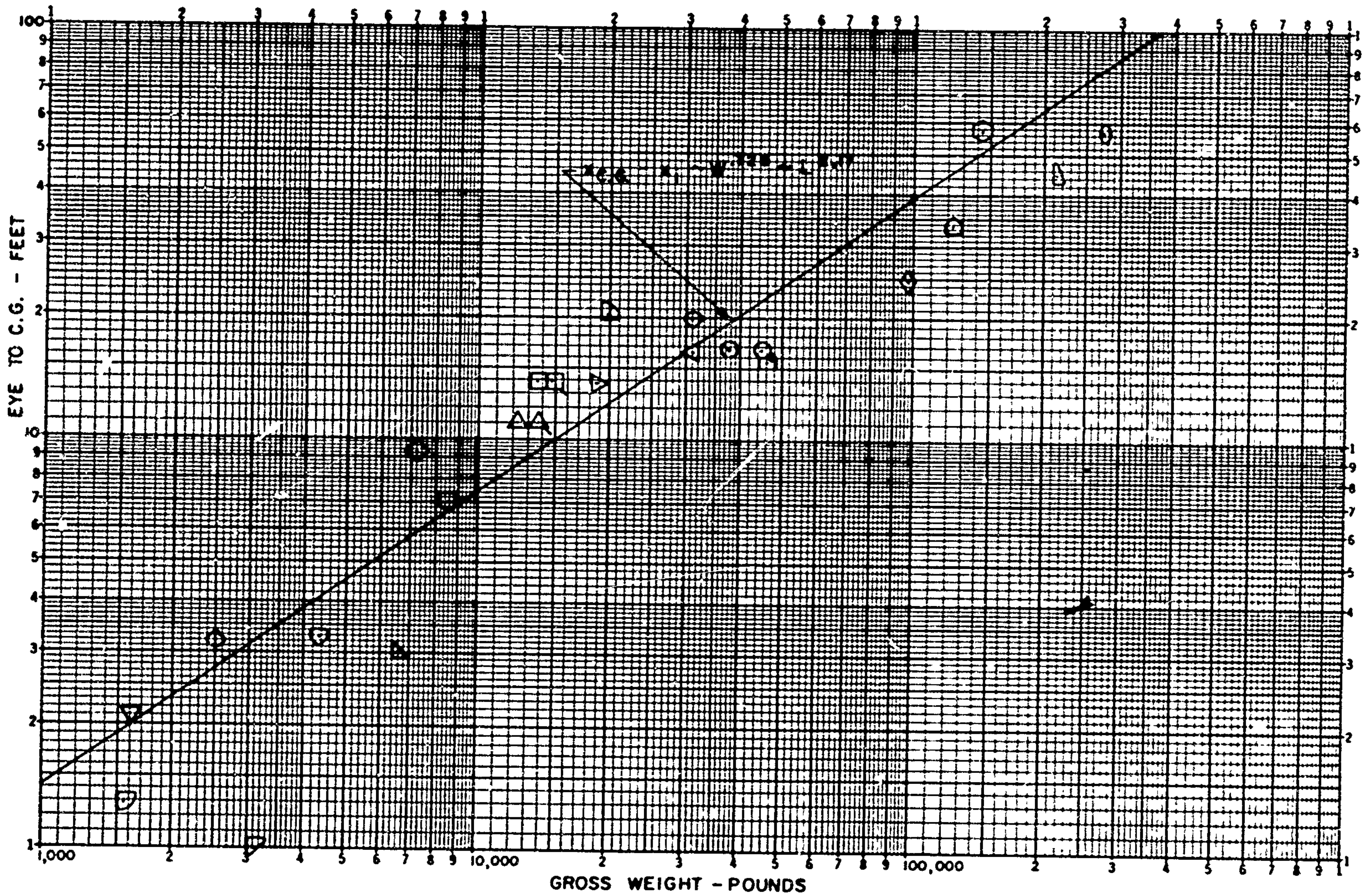

Figure 19 - Longitudinal Distance from Pilot's Eye to Vehicle Center of Gravity

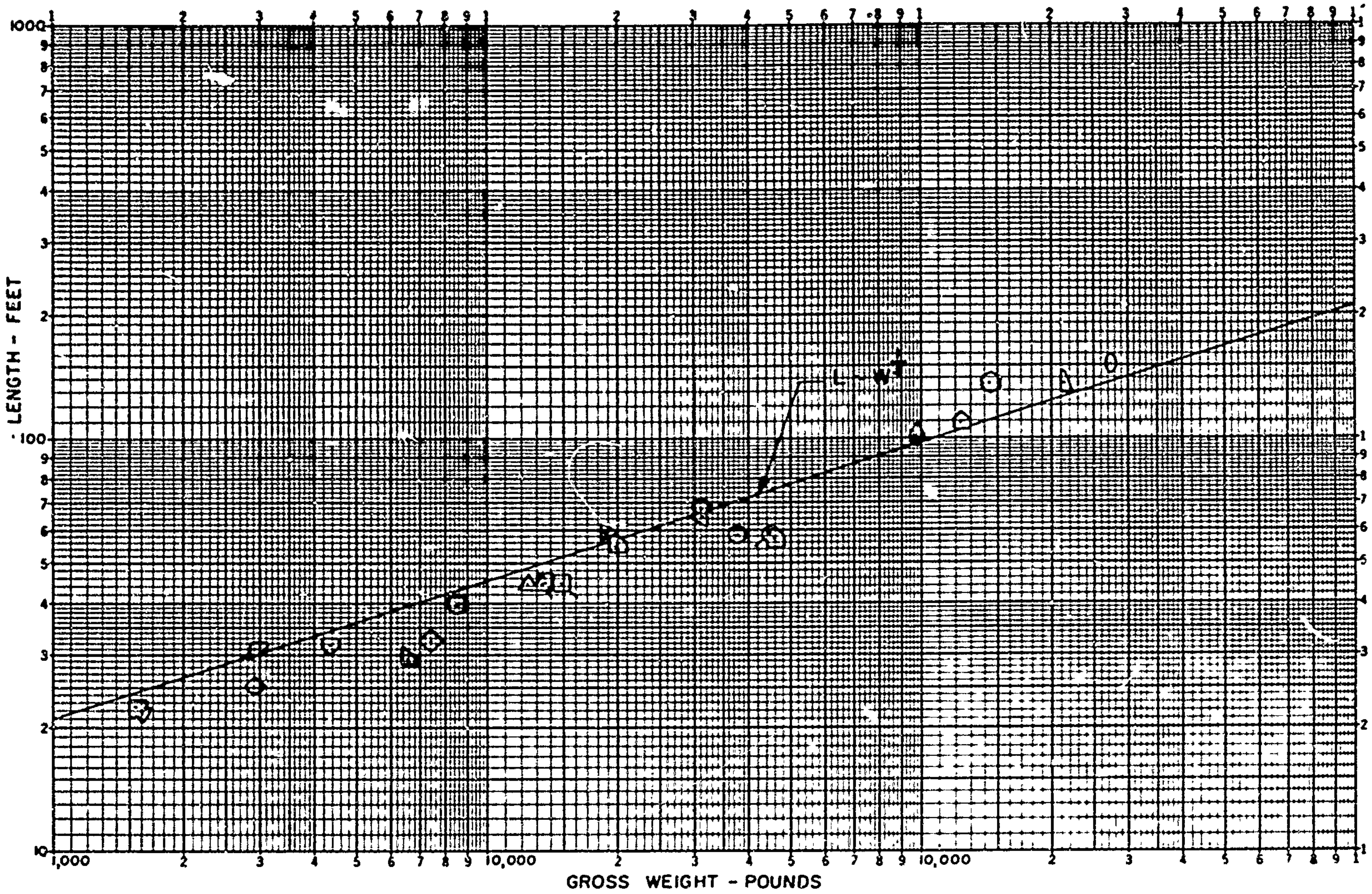

Figure 18 - Vehicle Length

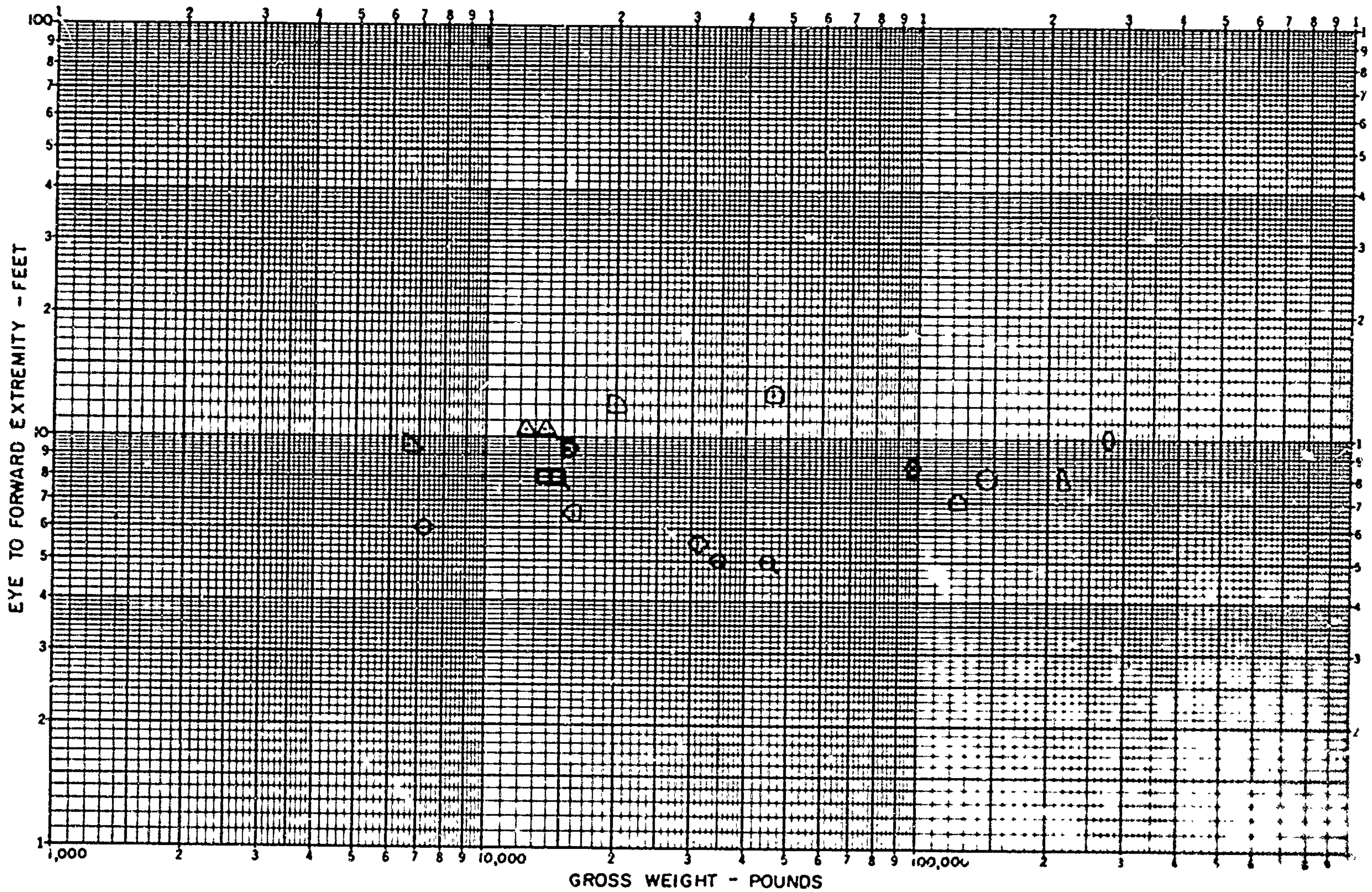

Figure 21 - Distance from Pilot's Eye to Vehicle Forward Extremity

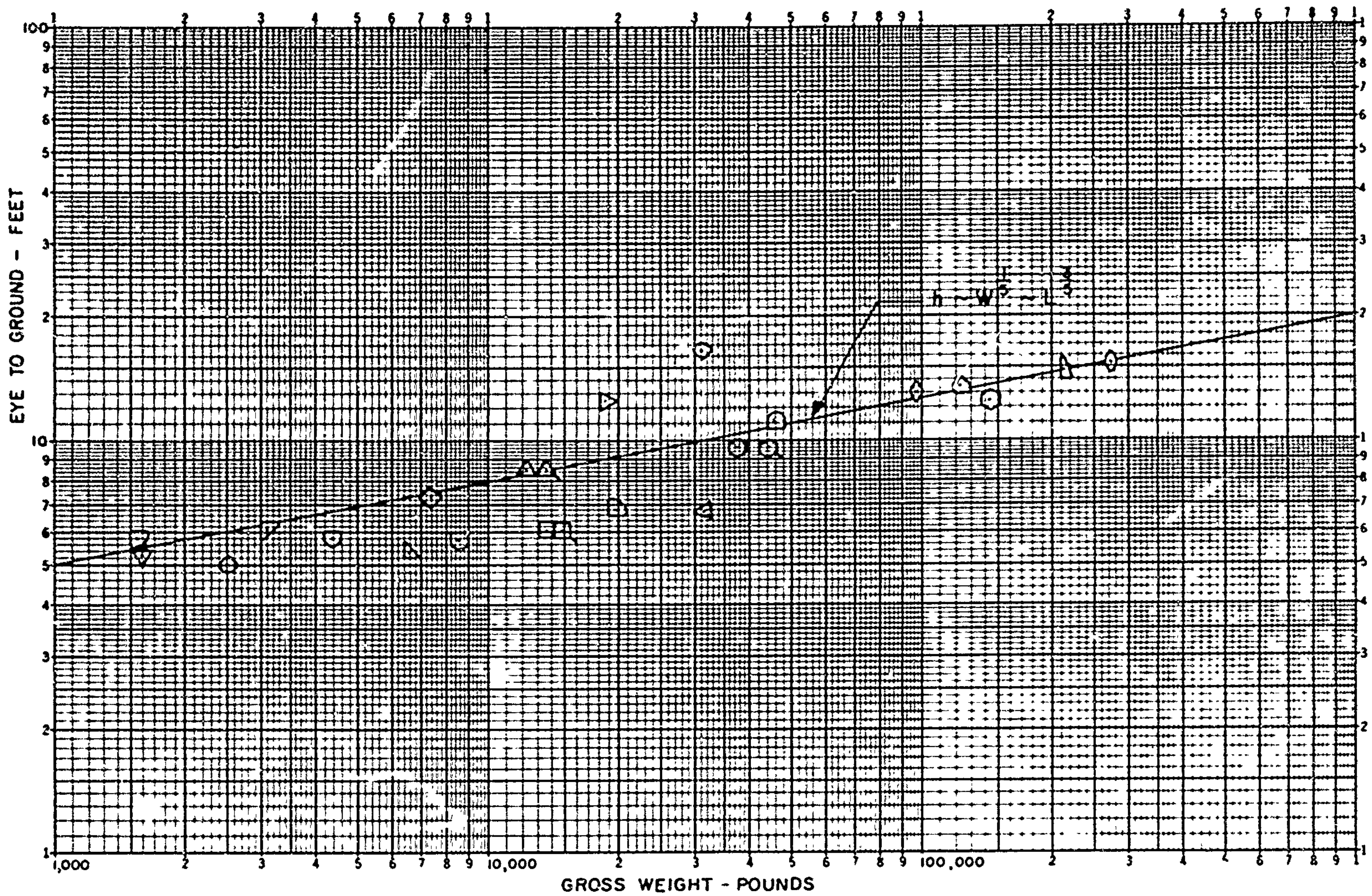

Figure 20 - Distance from Pilot's Eye to Ground (Vehicle on Ground)

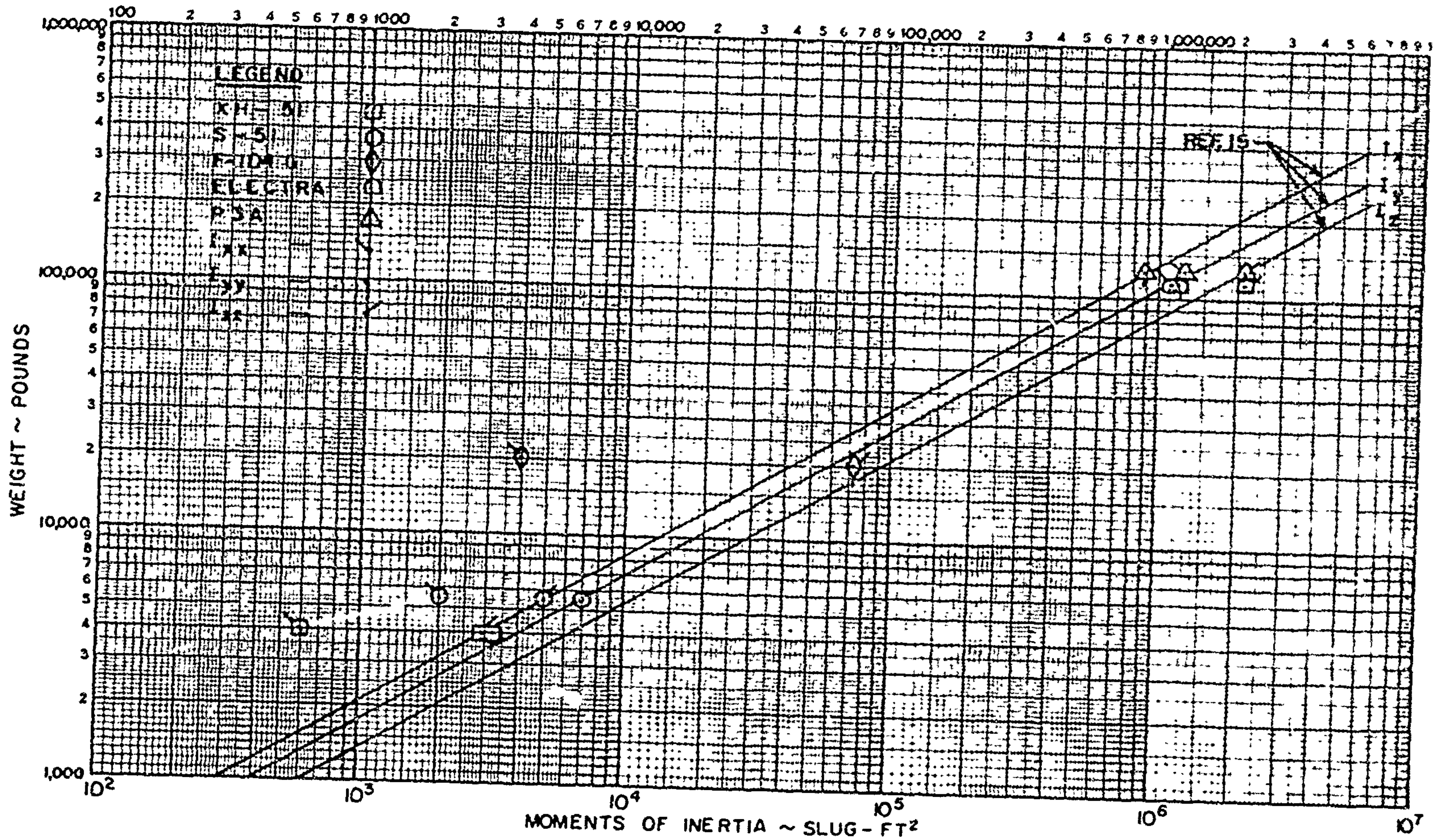

Figure 23 - Moments of Inertia

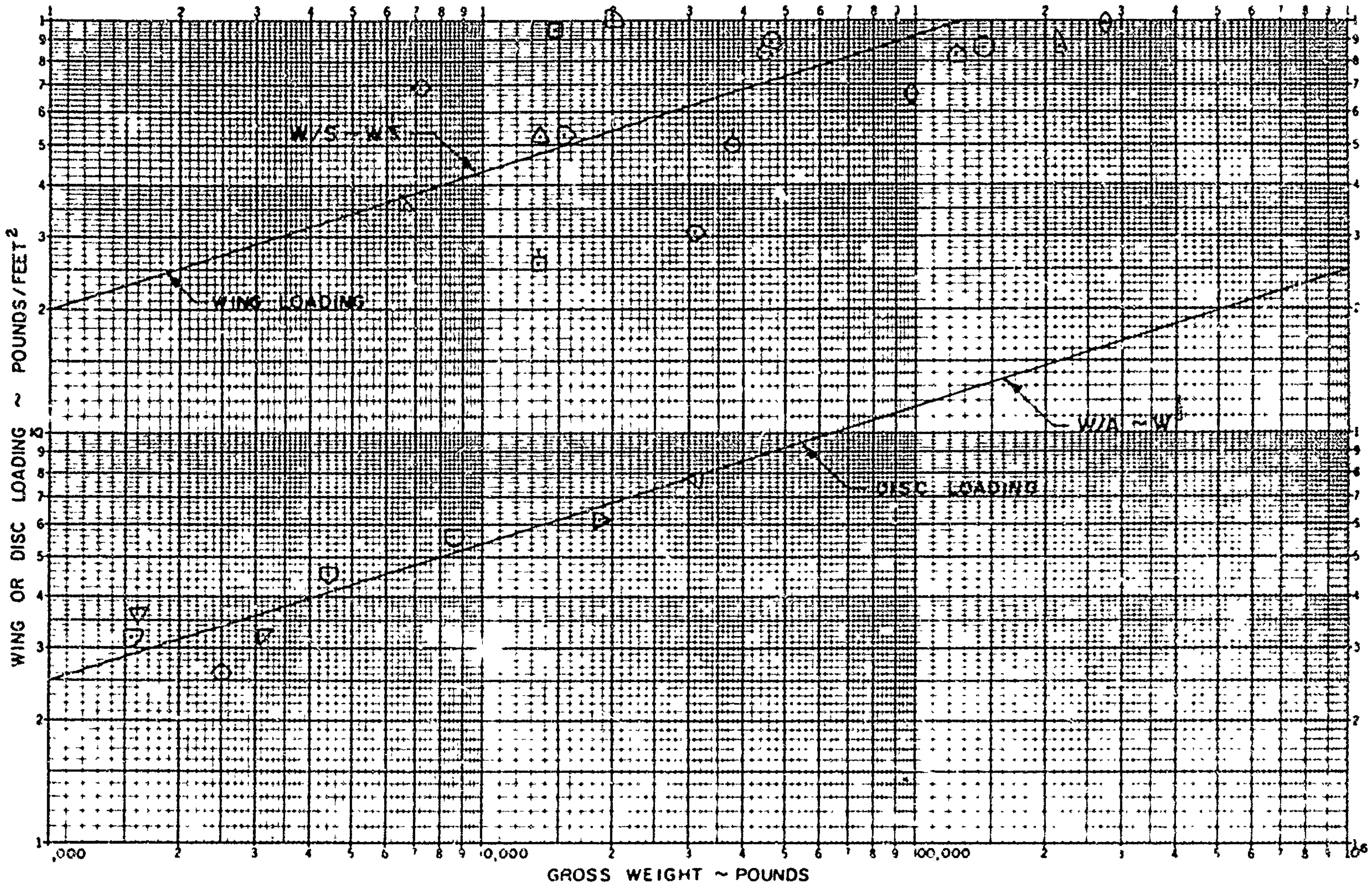

Figure 22 - Wing Loading and Disc Loading

APPENDIX III

HUMAN FACTORS

1. Pilot's Perception

The sensory information the pilot uses to direct the vehicles under discussion is primarily visual although many other clues are helpful. The threshold of the ability to judge velocity relative to distance of the observer from the moving object is described in Reference 16, Figure 10, as a function of the visual angle subtended by the target. The figure shows that the minimum perceptible rate lies between 0.15 and 0.30 feet per second per foot when the included angle is between 20 and 130 degrees.

The ability to estimate distance based on the known size of the object is shown in Reference 16, Figure 9. These data indicate that the error in estimating distance is between 15 percent less and 20 percent more than the actual distance, if the data on the 30 inch Mercury balloon are ignored (these data are within the tolerance below 400 feet). Obviously the minimum vehicle clearance with obstacles must provide for this error.

Figures 17, 19, 20, and 21 of Appendix II show the distance from pilot's eye to lateral extremity, distance from pilot's eye to vehicle center of gravity, distance from eye to ground (vehicle on ground), and the distance from eye to most forward vehicle extremity, respectively, as a function of vehicle gross weight. It may be seen from Figure 21 that distance from the eye to the forward extremity and the perception error are generally independent of vehicle size. The rearward distance to the eye is not given because vision is usually limited in this direction. Rearward obstacle distance can be maintained by selecting an operating site large enough for rearward clearance if proximity to forward obstacle is retained. Distance from the pilot's eye to the lateral extremity is half the span shown in Figure 17, Appendix II. The latter distance and accompanying perceptive error increase with vehicle weight.

The U. S. military helicopter specification (Reference 2, Sections 3.2.13, 3.2.14, 3.2.18, 3.3.19, and 3.6.1.1) specified increased longitudinal and lateral control power and damping for instrument flight conditions. These requirements were established from flight tests of instrument approaches. It is noted that these tests showed satisfactory descents up to approximately 12 degrees using only non-VTOL airplane type instrumentation and speeds of 30 to 60 knots. Deficiencies in both instrumentation and

handling qualities prevented obtainment of data for descents steeper than 12 degrees, transition to steep descent, and terminal near vertical descent (References 17, and 18). Analysis developed herein (pp. 59 and 60) indicates that the major deterrent to IFR flight is the long pilot reaction time associated with present methods and type of data presentation to the pilot.

2. Pilot Response Time

The time for a normal human pilot to respond to general stimuli (combined visual, aural, body pressure, etc.) is given in Reference 19, page 15, as 0.3 to 0.5 second. It is shown in Reference 16, page 321, Figure 11, that the response to purely visual observations (observer fixed) of angular motion between objects is considerably slower for the rates shown. Unfortunately the maximum rate is only 1.6 milliradians per second (0.1 degree per second), which requires a second for motion identification. Extrapolation of these data indicates that a response time of 0.5 second may be reached for angular rates between approximately 2 and 3 milliradians per second. No information could be obtained on time to identify a linear distance or motion.

For the purposes of this study it is assumed that perception-reaction times as short as 0.25 second are applicable for normal small-deflection control situations with experienced pilots. Additional lags are associated with larger control deflections and with adaptation to changed conditions.

Fundamental data on human perception and response are incomplete and appear to lack a broad statistical base. Additional information in this area is essential to the ultimate establishment of flying qualities criteria.

3. Vertical Velocity Control

The ability of the human operator to control vertical velocity has been determined experimentally to be a function of the vehicle delay or response time and the linear velocity damping as indicated by Reference 20. In order to operate without vertical damping it is necessary to reduce the control response time (time to reach 63 percent of acceleration commanded) to 0.2 second. Systems having control lags of larger than 0.4 second do not provide a satisfactory Cooper pilot's rating even with damping. Similar relations are developed analytically herein, as discussed in the section on pilot-vehicle compatibility.

APPENDIX IV

EXPERIMENTAL DATA ON DAMPING AND CONTROL POWER

A means of establishing general handling qualities criteria is by determination of parameters which provide vehicle motion characteristics with respect to control displacement identical to those of vehicles which have satisfactory qualities for the mission to which the criteria are to be applied. Control power/inertia in terms of control displacement, damping/inertia, derivatives of aerodynamic moments/inertia, derivatives of aerodynamic force/mass, control system time characteristics, and external disturbances are parameters which can define motion of the vehicle with respect to control input or external disturbances. These parameters will be used to describe handling qualities in the following discussion for the reasons given in the Introduction.

MINIMUM DAMPING/INERTIA RATIO

Flight tests of the X-14A and P-1127 VTOL airplanes, and the NASA Langley variable stability helicopter have demonstrated that VTOL vehicles can be flown satisfactorily without damping provided that nearly zero aerodynamic derivatives are provided inherently or artificially (as was the case on the helicopter). Additional tests, References 21, 22, 23 and 24, of several variable-stability helicopters and a fixed-base flight simulator have shown that the damping/inertia for a given pilot rating is a function of aerodynamic characteristics for hover and low speed flight. The above functions are illustrated graphically in Figure 24 for normal flight conditions with a Cooper pilot rating of 3.5 and in Figure 25 for emergency conditions with a rating of 6.5. The control forces and senstivities were adjusted to be near-optimum for minimum damping/inertia. Other control system characteristics, time lags, dead bands, etc., were considered as having been reduced to a level of insignificance.

The data shown in Figures 24 and 25 are believed to be unaffected by the 15-knot wind and turbulence simulated in the tests, as indicated by remarks in Reference 4, page 4, (NASA personnel indicate tests have been made of X-14A in winds up to 25 knots without changes in pilot ratings) and comparison of results at other wind velocities, including zero, in Reference 24, Figure 12. It may be noted that the Reference 24 data show an increasing effect of wind and turbulence above 15 knots. Hence the data of Figures 24 and 25 are considered satisfactory maneuver

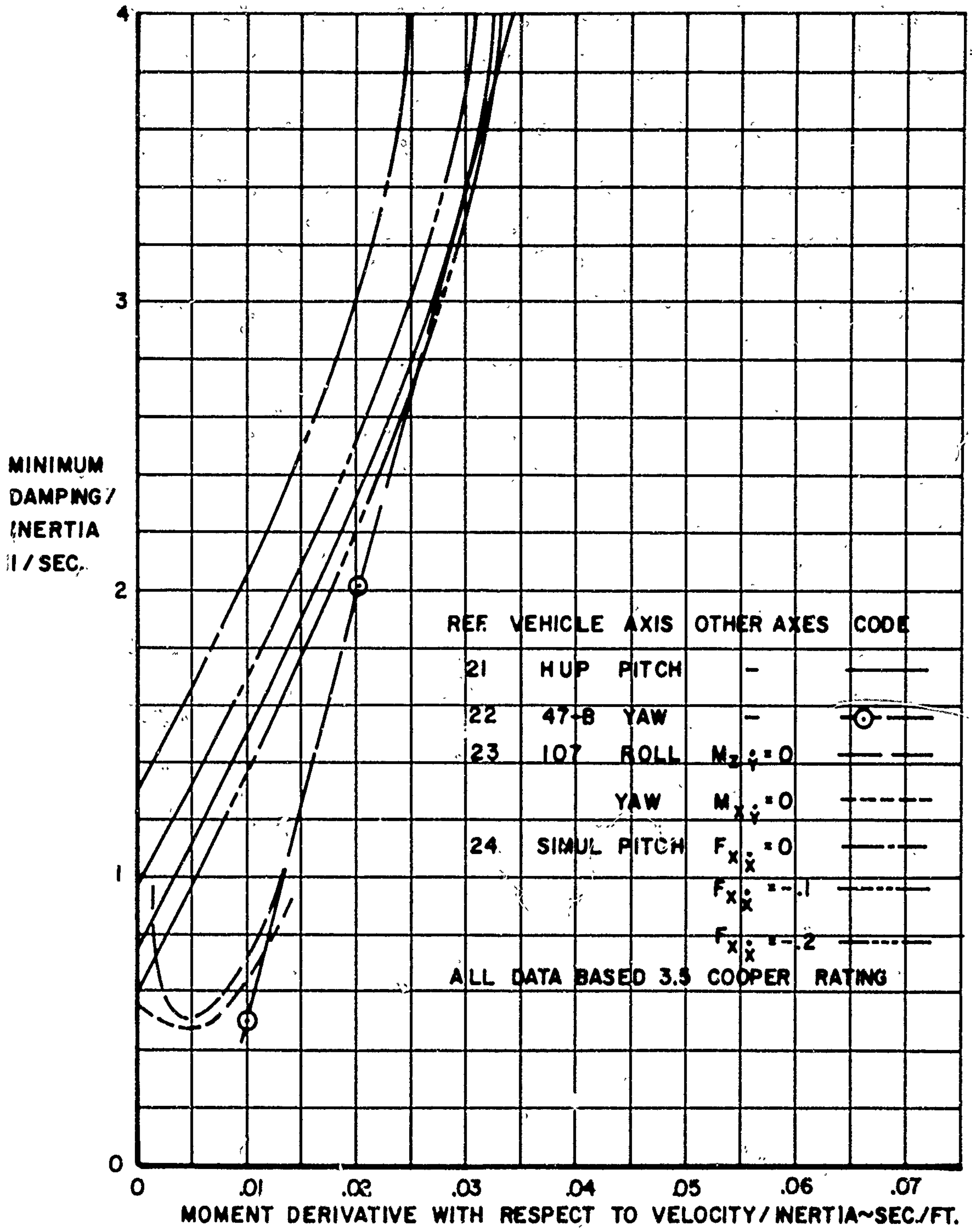

Figure 24 - Minimum Damping/Inertia, Normal

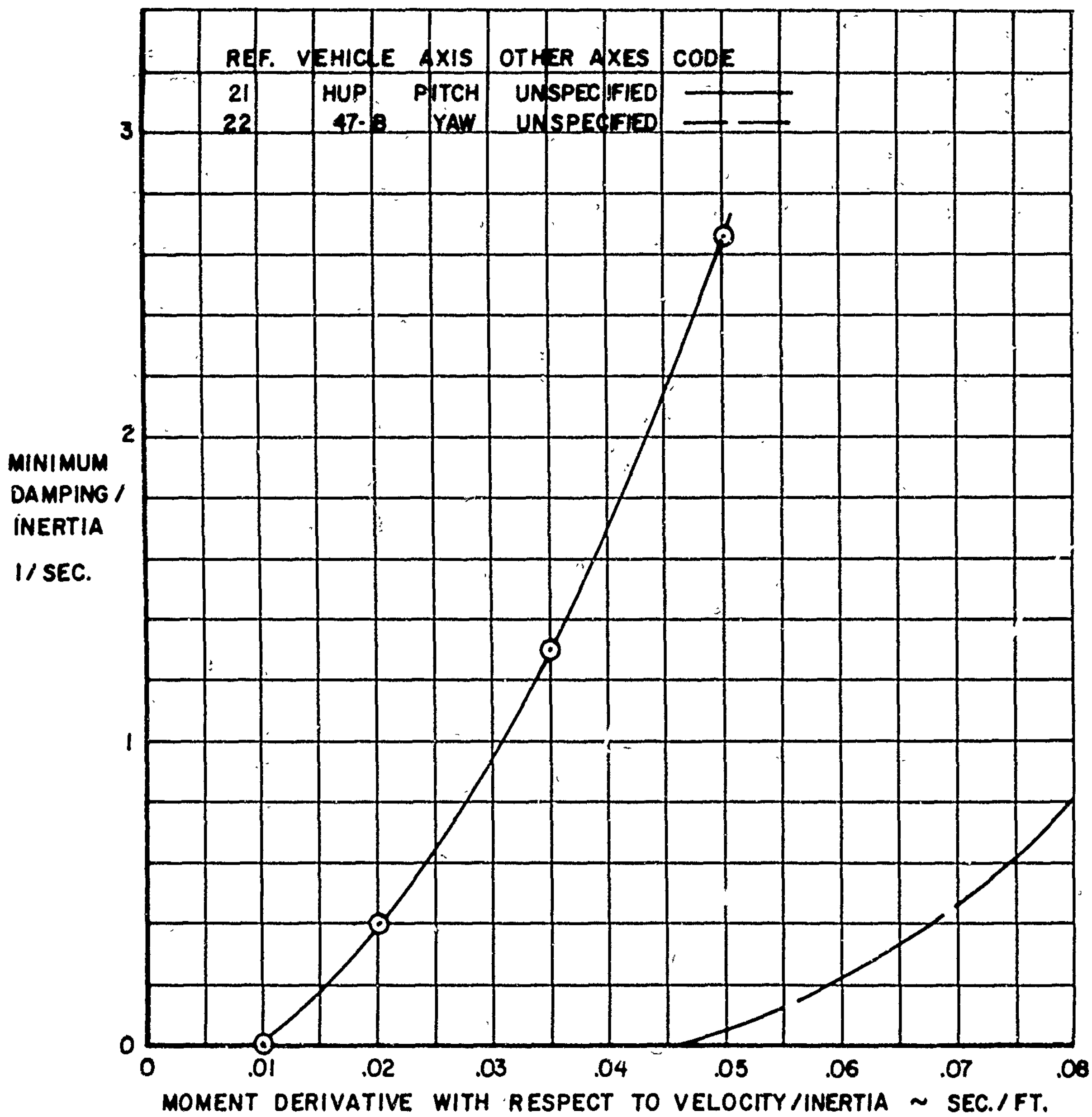

Figure 25 - Minimum Damping/Inertia, Emergency

criteria, adequate for winds up to 15 knots plus gusts up to at least 21 knots.

The damping/inertia of Figures 24 and 25 are strongly influenced by the aerodynamic derivative with respect to velocity/inertia and to a lesser extent by aerodynamic force derivative with respect to velocity/mass. The latter quantity reduces the required damping since aerodynamic force, in this case drag, actually is a damping force. The moment derivative, on the other hand, increases the required damping since the pilot's task is increased by having to cope with an uncommanded attitude change.

It is surprising that the damping/inertia requirements for the pitch axis (Figures 24 and 25) are higher than for roll and yaw. This difference may be caused by interaction of other unspecified aerodynamic derivatives or variations in pilot's ratings. It is cautioned that the data from Reference 24 are from a fixed base simulator, therefore lack motion cues.

It is believed that the relationships shown in Figures 24 and 25 are independent of size. However, the moment derivative with respect to velocity/inertia for geometrically similar vehicles is being reduced rapidly with size:

$$M_V/I \sim L^3/L^5 \sim 1/L^2 .$$

Hence the minimum damping/inertia may also be reduced with size until minimum values are reached.

DESIRED CONTROL POWER/INERTIA RATIO

Desired control power/inertia corresponding to minimum or near-minimum values of damping/inertia appears to be a function of the damping/inertia as indicated by flight and simulation tests for hover and low speeds, References 4, 17, 21, 22, 23, and 24. The test data and trends from these tests are shown in Figure 26 for normal operations corresponding to a Cooper rating of 3.5 and Figure 27 for an emergency condition with a rating of 6.5. Most of these data were obtained simultaneously with values illustrated in Figures 24 and 25, therefore are subject to the remarks given in the previous section. The points taken from tests not having data shown in Figures 24 and 25, however, appear to satisfy the same qualifications.

The trend lines shown in Figures 26 and 27 indicate that the desired control power/inertia increases in proportion to increase of damping/inertia, tending to maintain angular displacements constant for short time control inputs (these trends do not appear to maintain constant angular accelerations or rates) as would be expected. The test data

points do not show significant deviation from the trend lines with respect to vehicle size (unfortunately the variation in size is insufficient to be conclusive), type (jet VTOL, and single and tandem rotor helicoptors are represented), or axis.

In general the plots of control power/inertia versus damping/inertia from which desired control power/inertia in Figures 26 and 27 were obtained, indicate that desired values may be varied plus or minus ten percent without appreciably reducing the Cooper ratings. Vehicles designed to have more control power/inertia than that corresponding to minimum damping/inertia given in Figures 24 and 25 (as may be the case for combat type vehicles in order to achieve more agility), should be provided with higher damping/inertia corresponding to the values in Figures 26 and 27. This will insure good handling qualities and prevent oversensitivity. Higher angular accelerations and rates will be available because desired control power/inertia increases more rapidly than the damping/inertia while providing satisfactory damping.

Since the minimum damping/inertia tends to be reduced with size down to ultimate values (as shown in a previous section) and the control power/inertia is proportional to damping/inertia, the control power/inertia should also diminish with size until minimum values are reached. No flight test data are available on the effect of winds and gusts above 25 knots. Limited simulator data with winds and gusts above 25 knots are shown in Reference 24, Figure 12.

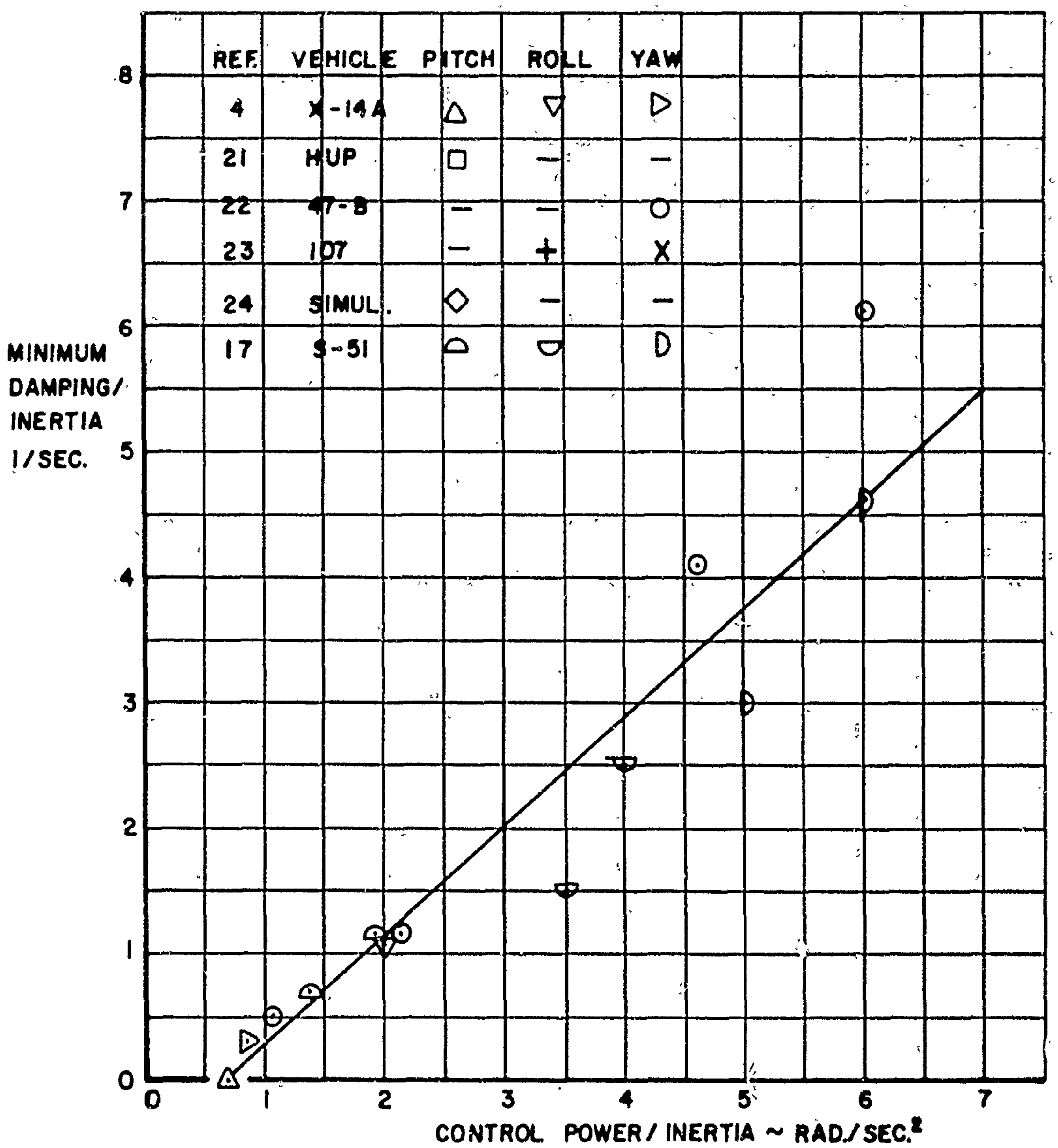

Figure 26 - Desired Control Power/Inertia, Normal

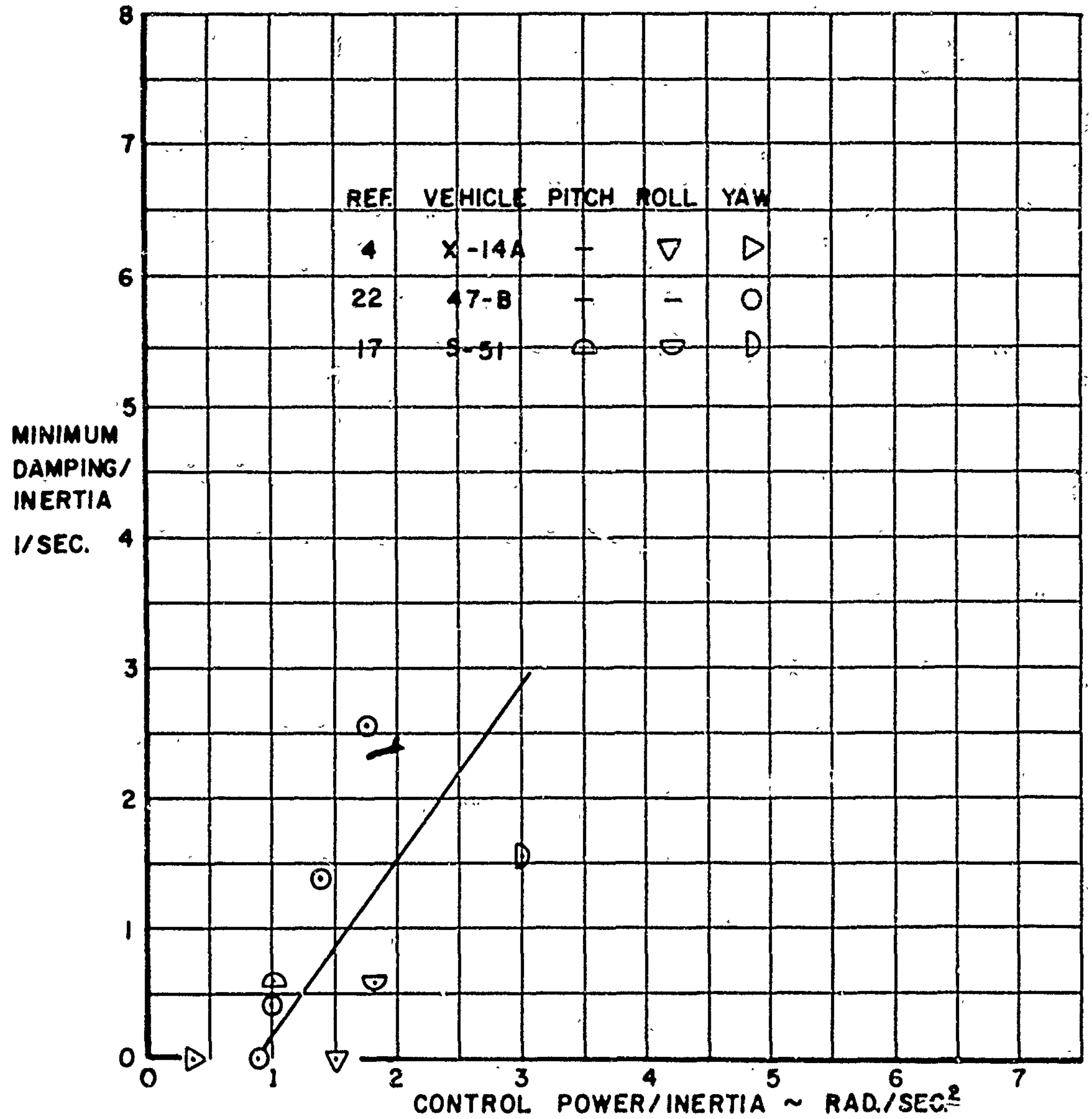

Figure 27 - Desired Control Power/Inertia, Emergency

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A fundamental study of the effects of vehicle size (as defined by characteristic linear dimension) on handling qualities of jet and helicopter type VTOL aircraft at hover and low speeds is presented. The effects of size on vehicle handling qualities capability and pilot-vehicle compatibility are developed. Consideration is given to the pilot as an adaptive nonlinear servo.

The study indicates that:

1. Control power/inertia and damping/inertia tend to decrease with size.
2. Final angular rates except for tail rotor helicopters in yaw are relatively invariant with size.
3. Characteristic time to make final angular rate increases with size.
4. Linear acceleration and motions are nearly invariant with size.
5. Effects of external disturbances and trim changes with speed on jet VTOL vehicles decrease at least as rapidly as control power/inertia.

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